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SYSTEM-OF-SYSTEMS TEST PLANNING IN A COMPLEX JOINT ENVIRONMENT

by

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June 2007

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13. ABSTRACT (maximum 200 words)

Force Transformation requires a much greater emphasis on testing joint warfighting capabilities. A unique challenge in assessing the effectiveness and suitability of systems in the joint environment is the multitude of possible interactions and outcomes in a system-of-systems construct. Because of resource constraints and the complexity of conducting live, virtual, and constructive testing in a joint mission environment, the Joint Test and Evaluation Methodology (JTEM) program is interested in determining if analytical techniques, like Modeling and Simulation, can be applied to understand the relationship between system-of-systems performance and joint mission effectiveness. As a proof of concept, a Network Enabled Weapon (NEW) was chosen as a framework for this study. This thesis uses an agent-based distillation, which is a type of computer simulation, to model the critical factors of interest in a NEW engagement without explicitly modeling all of the physical details. Using cutting-edge experimental design techniques, the computer model was run many tens of thousands of times, with the results being analyzed to determine the critical parameters required for mission success. The analysis determined key interactions in NEW system performance and provides JTEM with a framework for efficiently conducting testing in a live environment. Specifically, the results indicate sensor range of a third-party ground controller, target speed, NEW impact radius, and weapon accuracy as the key factors affecting system performance.

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SYSTEM-OF-SYSTEMS TEST PLANNING
IN A COMPLEX JOINT ENVIRONMENT

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Submitted in partial fulfillment of the
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ABSTRACT

Force Transformation requires a much greater emphasis on testing joint warfighting capabilities. A unique challenge in assessing the effectiveness and suitability of systems in the joint environment is the multitude of possible interactions and outcomes in a system-of-systems construct. Because of resource constraints and the complexity of conducting live, virtual, and constructive testing in a joint mission environment, the Joint Test and Evaluation Methodology (JTEM) program is interested in determining if analytical techniques, like Modeling and Simulation, can be applied to understand the relationship between system-of-systems performance and joint mission effectiveness. As a proof of concept, a Network Enabled Weapon (NEW) was chosen as a framework for this study. This thesis uses an agent-based distillation, which is a type of computer simulation, to model the critical factors of interest in a NEW engagement without explicitly modeling all of the physical details. Using cutting-edge experimental design techniques, the computer model was run many tens of thousands of times, with the results being analyzed to determine the critical parameters required for mission success. The analysis determined key interactions in NEW system performance and provides JTEM with a framework for efficiently conducting testing in a live environment. Specifically, the results indicate sensor range of a third-party ground controller, target speed, NEW impact radius, and weapon accuracy as the key factors affecting system performance.

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THESIS DISCLAIMER

The reader is cautioned that the computer model presented in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logical errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

Additionally, the intent of this effort was to gain insight into factors affecting overall system performance. The research was not conducted, nor was the model designed, to prove or demonstrate the capabilities of specific weapon systems used as the framework for characteristics of the simulated entities. As such, the reader should not use this research as a measure of assessing the effectiveness or suitability of weapon systems currently under development.

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LIST OF ACRONYMS

ABM	Agent-Based Modeling
C2	Command and Control
CAOC	Combined Air Operations Center
CAP	Combat Air Patrol
CAS	Close Air Support
CJCS	Chairman, Joint Chiefs of Staff
CoComs	Combatant Commanders
DoE	Design of Experiments
DOT&E	Director, Operational Test and Evaluation
DP	Design Point
DoD	Department of Defense
FOV	Field of View
HVT	High-Value Target
IFTU	In-Flight Target Update
JCIDS	Joint Capabilities and Integration Development System
JTAC	Joint Terminal Attack Controller
JMe	Joint Mission Effectiveness
JME	Joint Mission Environment
JTEM	Joint Test and Evaluation Methodology
JV 2020	Joint Vision 2020
M&S	Modeling and Simulation
MOE	Measure of Effectiveness
MTDF	Multi-Target Degradation Factor
NEW	Network Enabled Weapon
NOLH	Nearly Orthogonal Latin Hypercube
NPS	Naval Postgraduate School
OT&E	Operational Test and Evaluation
Pd	Probability of Detection
PGM	Precision Guided Munition

Pk	Probability of Kill
QDR	Quadrennial Defense Review
RDT&E	Research, Development, Test, and Evaluation
SDB II	Small Diameter Bomb, Increment II
SecDef	Secretary of Defense
SME	Subject Matter Expert
T&E	Test and Evaluation
TLE	Target Location Error
TST	Time-Sensitive Target
TTPs	Tactics, Techniques, and Procedures
UAV	Unmanned Aerial Vehicle
WCN	Weapon Control Network

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This research would have never finished on time without the patient guidance of my advisor, Dr. Tom Lucas. His advice, intellect, and mentorship throughout made the grueling process bearable and even enjoyable at times. I cannot begin to thank him enough for providing me with the tools (mental and physical) required to complete this endeavor. Of equal importance were the expert computer programming skills of Steve Upton, with whom I coordinated endlessly during the development of the simulation model. None of the analysis conducted herein would have been possible without his professional efforts. Thank you, Steve.

I would also be remiss if I did not thank the many individuals who guided and supported this research. Of note are: Colonel Eileen Bjorkman, Lieutenant Colonel Stafford Maheu, Tom Thacker, Major Mark Raffetto, and Dr. Gary Horne. Either through funding, information, inspiration, or a combination thereof, each of you has graciously offered your time and energy toward making this thesis a success.

Finally, I want to thank Richard Mastowski for his assistance with editing and formatting. Your efforts allowed me to focus on the important aspects of content, instead of worrying about perfect alignment and grammar.

To my daughters Heidi and Hope—Daddy loves you.

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EXECUTIVE SUMMARY

Joint operations have become the mainstay of warfighting. Force Transformation requires the Test and Evaluation (T&E) community to place a much greater emphasis on testing joint warfighting capabilities. A unique challenge in assessing the effectiveness and suitability of systems in the joint environment is the multitude of possible interactions and outcomes in a system-of-systems construct. New and developing acquisition programs rely on interfaces with existing or future systems, quite possibly from separate services, to achieve mission success. Because of resource constraints and the complexity of conducting live, virtual, and constructive testing in a joint mission environment, the Joint Test and Evaluation Methodology (JTEM) program is interested in determining if analytical techniques, like Modeling and Simulation (M&S), can be applied to understand the relationship between system-of-systems performance and joint mission effectiveness. As a proof of concept for investigating this possibility, Network Enabled Weapons (NEWs) was chosen as a framework for further study. The NEW concept centers on the ability to identify, engage, and attack moving targets, within moments of their identification, through the use of in-flight target updates (IFTUs) across a Weapon Control Network (WCN).

As acquisition systems like NEW are required to conduct more testing in the context of a joint mission, it will be essential that these tests be as efficient and useful as possible. With the complexity of the joint test environment, M&S is one of the most effective tools to help understand the environment, design an efficient and useful test, and to help investigate robust possibilities in the use of forces to accomplish operational tasks. This thesis used an agent-based distillation, which is a type of computer simulation, to model the critical factors of interest in combat without explicitly modeling all of the physical detail. Agent-Based Modeling (ABM) refers to a type of simulation made up of agents (or entities) that behave autonomously. These agents possess simple internal rule-sets for decision making, movement, and action. When combined with other entities in the model and subjected to stochastic conditions, the agents interact in ways

that are often reflective of large-scale system behavior.[1] In close coordination with JTEM and program offices responsible for networked weapons, the author and the model developer worked through numerous iterations of programming and debugging over the course of six months in order to refine the model and improve its validity.

As with many complex endeavors, military conflicts typify an environment of autonomous or semiautonomous agents, uncertainty in behavior and outcomes, a wide range of operational inputs, and complex interactions between entities.[2] The combination of ABM with Data Farming offers an exploratory, analytical approach to broadly consider uncertainties associated with elements of warfare that might otherwise be too costly or time intensive to study with other means.

Data Farming involves the exploration of simulation models across a wide range of settings for the agents' characteristics and running the model a statistically significant number of times.[3] Rather than taking a "trial and error" approach to experimental design (be it live or in the M&S environment), researchers often use specialized techniques to organize the myriad of possible parameter settings. The overall objective of the design is to maximize the information gained from a limited number of experimental runs. In his Ph.D. Dissertation at the Naval Postgraduate School, LTC Thomas Cioppa, USA, provides an approach to experimentation geared toward addressing the issue of efficient design and analysis techniques for complex simulation models. His research indicates that the use of orthogonal, or nearly orthogonal, Latin hypercubes with excellent space-filling properties enable efficient exploration of simulation models.[4] Unlike traditional factorial designs, which test only a few factors at a minimum number of levels, a space-filling design explores a broad landscape of factor settings, as indicated in Figure ES-1.

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[1] Susan M. Sanchez and Thomas W. Lucas, "Exploring the World of Agent-Based Simulations: Simple Models, Complex Analyses," Proceedings of the 2002 Winter Simulation Conference, December 2002, p. 1.

[2] Thomas M. Cioppa, Thomas W. Lucas, and Susan M. Sanchez, "Military Applications of Agent-Based Simulations," Proceedings of the 2004 Winter Simulation Conference, December 2004, p. 1.

[3] Gary Horne and Ted Meyer, "Data Farming: Discovering Surprise," Proceedings of the 2004 Winter Simulation Conference, December 2004, p. 2.

[4] Thomas M. Cioppa, LTC, USA, "Efficient Nearly Orthogonal and Space-Filling Experimental Designs for High-Dimensional Complex Models," Ph.D. Dissertation, Naval Postgraduate School, Monterey, CA, September 2002, p. 9.

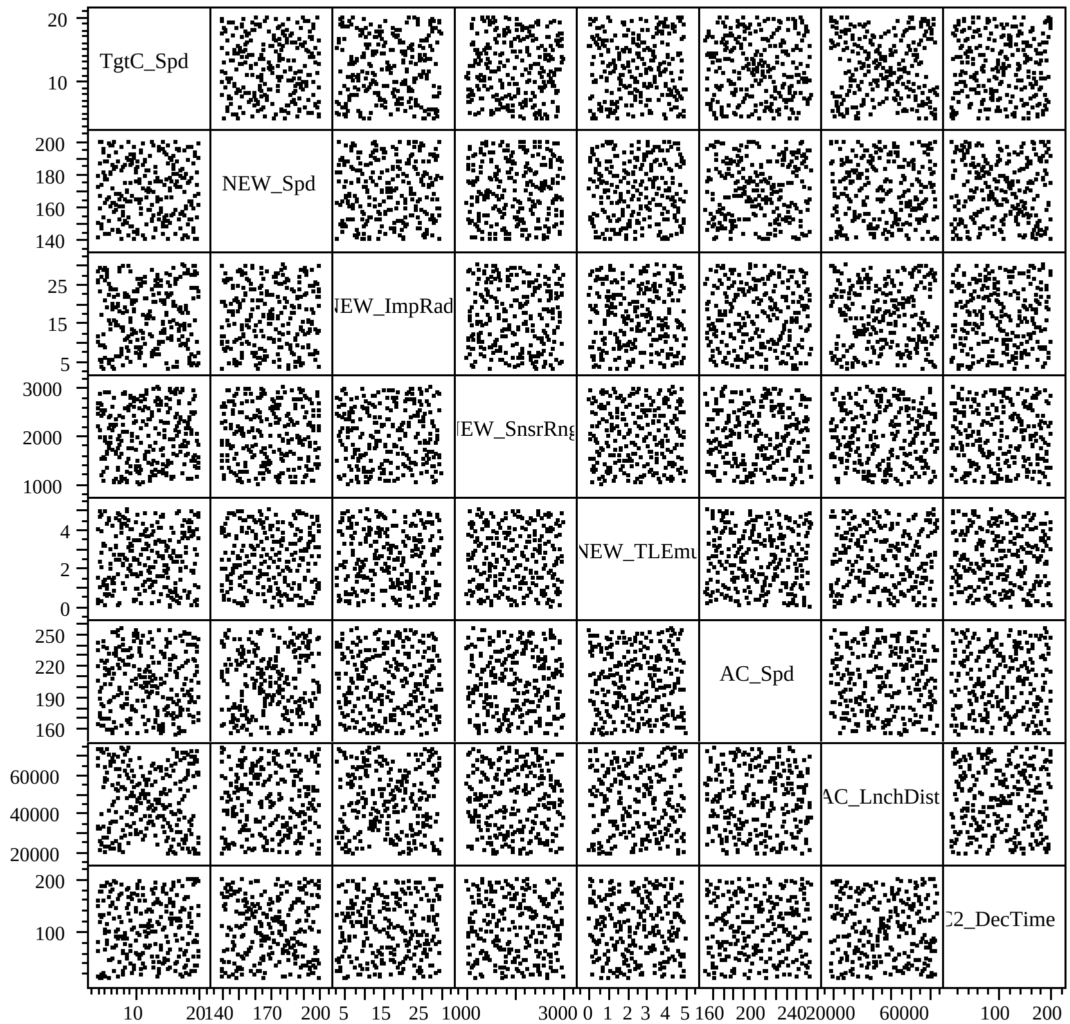

Figure ES-1. Scatterplot Matrix for a Selection of Eight Factors Exhibiting Excellent Space-Filling Properties of the Design.

Figure ES-1 shows a two-dimensional projection for eight of the factor combinations in the single target (21-factor) design and exhibits outstanding space-filling properties. As a separate indicator of design efficacy, the orthogonality of the design improves the analysis of model results by decreasing correlation among regression coefficient estimates, and by allowing investigation of multiple high-order interactions, nonlinear relationships, and discontinuities in the response.[5]

[5] Thomas M. Cioppa, LTC, USA, “Efficient Nearly Orthogonal and Space-Filling Experimental Designs for High-Dimensional Complex Models,” Ph.D. Dissertation, Naval Postgraduate School, Monterey, CA, September 2002, p. 21.

For seven factors, this design approach allows the exploration of model effects across 17 uniformly distributed factor settings, in as few as 17 model runs. In comparison, a three-level, full factorial design of seven factors requires 3^7, or 2,187 model runs, and would only examine three levels of each factor. When considering that this research examined the effects and interactions of more than 20 factors in each design, the significance is the difference between running 100 replications on a single laptop computer in five hours, or waiting until the sun burns out and never seeing the results.

Using these cutting-edge, experimental design techniques, the computer model was run many tens of thousands of times, with each parameter having 257 settings varied uniformly over operationally viable ranges. The results were analyzed to determine the critical parameters required for mission success. In the case of a single moving target, indicative of a wheeled or tracked vehicle, the analysis indicates a significant time-distance interaction between the sensor range of the ground-based Joint Terminal Attack Controller (JTAC) and the speed of the target. Specifically, when the target speed is less than 13.2 meters/sec (approximately 30 mph) and the JTAC sensor range exceeds 2,117 meters, the model indicates an 80% improvement in target kills, regardless of the other parameter settings. Moreover, when a combination of these two parameters is constrained across a realistic, but time-sensitive range, the model indicates that the amount of time taken by the decision authority to issue a Close Air Support (CAS) request and the speed at which the launch aircraft flies to engage the target provide the most improvement in mission success.

This result is illustrated through use of a partitioning tree in Figure ES-2. The partitioning (or regression) tree is a statistical analysis approach aimed at identifying the most critical factors affecting the response variable—in this case, the proportion of target kills. Each block lists the factor name, the total number of data points contained in the branch, and the mean value and standard deviation of those points. To perform each "split" of the tree, the statistical software recursively divides the factor that most significantly separates the means by examining the differences in sums of squares. As shown in the figure, the ratio of JTAC sensor range to target speed is the most critical factor in the model for the first two splits (albeit at different threshold values). If the ratio is between 197 and 305 seconds, then Command and Control decision time and aircraft speed account for the next significant splits, at the values shown. It should be noted that while the ratio variable of range to speed provides a meaningful way to conduct the present analysis, the variable itself is notional in the sense that it depends on the context in which the specific scenario was developed.

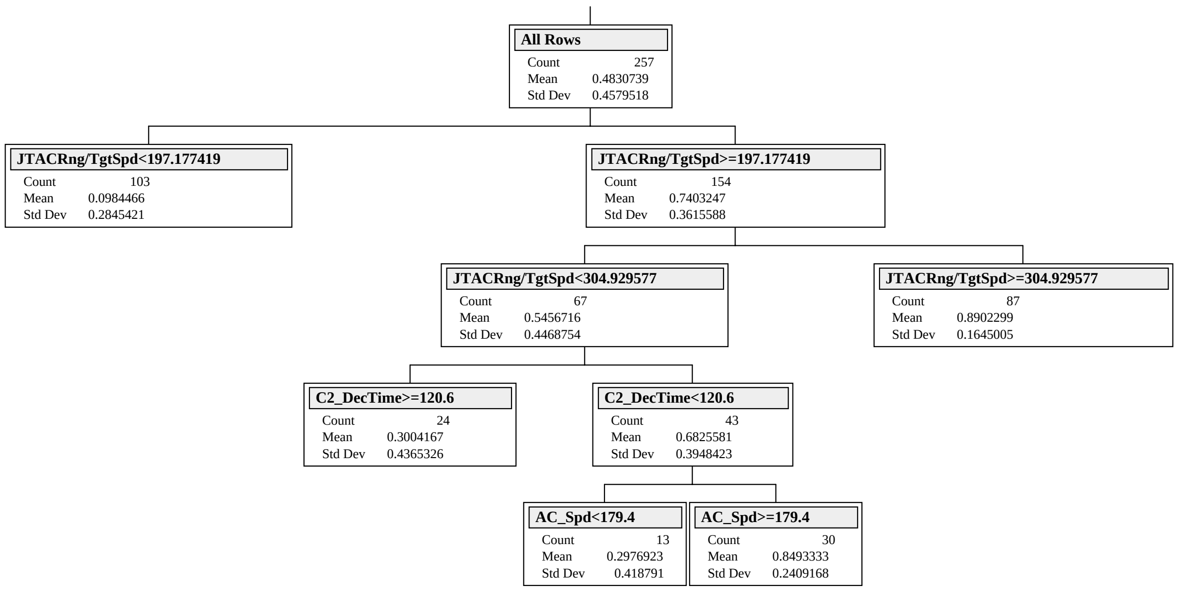

Figure ES-2. Partition Tree for the Single Mobile Target Scenario with Number of Kills as the Response and a New Explanatory Factor Created from Dividing JTAC Sensor Range by the Target Speed.

To test the system's ability to engage a subsequently identified high-value target (HVT)—possibly with a redirect of a NEW already in flight—scenarios were run with two targets in the battlespace. The second target possesses the characteristics of a dismounted individual on patrol. The model indicates different results for the kill rate of the HVT, depending on whether or not the launch aircraft contains a load of two NEWs or just one. In the case of one weapon, for a JTAC sensor range of less than two kilometers, the kill rate of the HVT is shown to improve by nearly 82% if the IFTU interval is less than 50 seconds. In the case where two weapons are available, the most important factors affecting the HVT kill rate are specific to the weapon itself. Namely, if the impact radius exceeds 5.4 meters and the probability of kill for a target within the blast radius is greater than 0.92, then the overall kill rate approaches 95%.

While relatively simple in design, the simulation model provides a realistic depiction of operational scenarios and the interactions of systems within the NEW construct. Over the course of this research, the author consulted with JTEM personnel and subject matter experts within the NEW development community to discuss model functionality and the ranges of settings for model parameters. The author and the model co-developer worked through numerous iterations of programming and debugging over the course of six months in order to refine the model and improve its performance.

The results of the analysis determined key interactions in NEW system-of-systems performance. Additionally, when considered in context of the scenarios developed, the model provides insight for program managers trying to understand the required performance characteristics of systems in development. Most importantly, the research indicates that ABM, especially when combined with efficient design principles, can yield a method to quickly analyze a complex system-of-systems construct and provide JTEM with a framework for effectively conducting testing in a live environment.

I. INTRODUCTION

> *We must, therefore, be confident that the general measures we have adopted will produce the results we expect.*

–Karl von Clausewitz

A. BACKGROUND

Joint Vision 2020 was published by the Joint Chiefs of Staff to describe the operational concepts necessary to achieve success in our Nation's future conflicts. An uncertain future creates a broad range of threat possibilities and requires an investment in technologies and new military capabilities.[6]

The Secretary of Defense's *Quadrennial Defense Review* (*QDR*), published 30 September 2001, indicates that the transformation required to meet future threats is neither an end point itself, nor a single weapon system or strategy. Rather, it is the process used to achieve warfighting capabilities and is based on the following four Transformational Pillars:

> Strengthening joint operations through standing joint task force headquarters, improved joint command and control, joint training, and expanded joint force presence policy;
>
> Experimenting with new approaches to warfare, operational concepts and capabilities, and organizational constructs such as standing joint forces through wargaming, simulations and field exercises focused on emerging challenges and opportunities;
>
> Exploiting U.S. intelligence advantages through multiple intelligence collection assets, global surveillance and reconnaissance, and enhanced exploitation and dissemination;

[6] Joint Chiefs of Staff, Joint Vision 2020, United States Department of Defense, Washington, D.C., June 2000, p. 1.

> <u>Developing</u> transformational capabilities through increased and wide-ranging science and technology, selective increases in procurement, and innovations in DoD processes.[7]

In line with the pillar of experimentation, the *QDR* further states: "While transformation offers U.S. forces the promise of revolutionary capabilities, the products of this transformation must be tested thoroughly before they are deployed."[8] In his National Military Strategy, the Chairman of the Joint Chiefs of Staff (CJCS) indicates that for the United States to maintain our advantage on the battlefield, we must transform our military by "combining technology, intellect and cultural changes across the joint community."[9] The roadmap for the future of the U.S. military is clearly one requiring a transformation of capability and a need to test our ability to achieve success in a joint environment.

Complexity arises because the systems participating in a joint mission will interact and evolve in ways that are not easily predictable. Systems are designed to meet specific requirements. Developmental testing and, to a degree, operational testing, are designed to evaluate whether the systems can meet those requirements. As those systems are given to operators for training and employment, they will find better ways to use the system's inherent capabilities. Operators will also find ways to work around capability limitations. Tactical decision makers will employ those systems in combinations and in conditions not anticipated by the designers and testers—often in response to changes in tactics of an evolving, adaptive adversary. This is especially true when different systems, with different capabilities, are employed in a joint environment.

B. TEST AND EVALUATION IN A JOINT ENVIRONMENT

Joint operations have become the mainstay of warfighting. Force Transformation requires the Test and Evaluation (T&E) community to place a much greater emphasis on

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[7] United States Department of Defense, Quadrennial Defense Review Report, Washington, D.C., 30 September 2001, p. 32.

[8] Ibid., p. 41.

[9] Chairman of the Joint Chiefs of Staff, National Military Strategy of the United States of America, United States Department of Defense, Washington, D.C., 2004, p. 15.

testing joint warfighting capabilities developed in response to the Joint Capabilities Integration and Development System (JCIDS) process. T&E must ensure that our combatant commanders (CoComs) can rely on equipment (existing and future) to operate together effectively without introducing problems to the warfighters.[10]

Conducting live testing is further complicated by the limitations of defense budgets. Of the over $439 billion in the 2007 Department of Defense (DoD) budget, a significant portion, about $73 billion is devoted to Research, Development, Test, and Evaluation (RDT&E). Only $181 million, about one-quarter percent of the RDT&E amount, however, is devoted to Operational Test and Evaluation (OT&E). This amplifies the fact that operational testing must be structured as efficiently as possible.[11]

In 2003, the Defense Science Board Task Force *Report on Enabling Joint Force Capabilities* stated:

> . . . a network-centric approach based on a jointly developed network architecture remains essential if we are to field forces that can (1) respond quickly to a wide range of contingency demands and (2) act decisively from the outset against adaptive and resourceful adversaries. This requires full-capability, highly integrated joint land, sea, air, and space forces.[12]

Figure 1 depicts the flow of guidance leading to the need for integrated testing in the joint environment. The *Transformation Planning Guidance*, published by the United States Secretary of Defense (SecDef) in April 2003, states:

> As the Department transforms to a joint concept-centric approach for operational planning and capabilities development, we need integrated architectures that define the specific parameters of the requisite joint capabilities. A Joint Test and Evaluation Capability is needed to test the

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[10] Director, Operational T&E, Testing in a Joint Environment Roadmap Strategic Planning Guidance, United States Department of Defense, Final Report, November 2004, p. vii.

[11] DoD budget data obtained from www.defenselink.mil/comptroller/defbudget/fy2007/index.html; site last accessed in May 2007.

[12] Defense Science Board, Report of the DSB Task Force on Enabling Joint Force Capabilities, August 2003, p. 1.

capabilities in a realistic joint environment. Test and evaluation in a joint context will reveal whether or not the integrated architectures present a viable application of warfighting capabilities.[13]

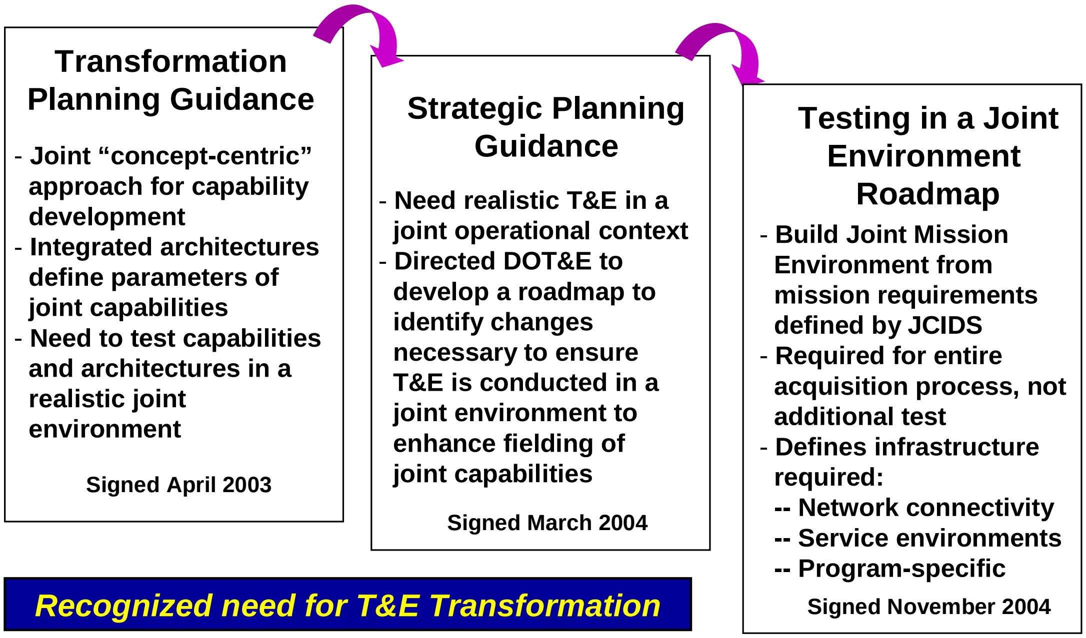

Figure 1. Building the Need for T&E Transformation[14]

The Strategic Planning Guidance in March 2004 further delineated the need for a transformation in T&E and instructed the Director, Operational Test and Evaluation (DOT&E), to conduct a study to develop a roadmap on the way ahead for T&E transformation.[15] This roadmap was signed and published in November 2004, and it addressed three major issues: (1) The need to construct a joint environment suitable for testing applications from the mission requirements defined by the JCIDS capability planning process; (2) the requirement to use this environment across the entire acquisition

[13] Secretary of Defense, Transformation Planning Guidance, United States Department of Defense, Washington, D.C., April 2003, p. 20.

[14] Eileen Bjorkman, Col, USAF, "JTEM Overview Briefing," March 2006, slide 3.

[15] Strategic Planning Guidance for FYs 2006-2011, CLASSIFIED; not releasable to the public.

process, not as an additional test requirement; and (3) the required infrastructure, to include network connectivity, service-environments, and program-specific modeling and simulation.[16]

C. JOINT TEST AND EVALUATION METHODOLOGY TEST CASE

Chartered by DOT&E with accomplishing the task of putting the roadmap into action, the Joint Test and Evaluation Methodology (JTEM) program was established in January 2006. Their overall goal is to develop a consistent approach to T&E in the joint environment. Among their main challenges are that processes and methods for designing and executing tests of system-of-systems are not well defined or understood, nor is there a clear understanding of how to assess system performance pertaining to capabilities supporting joint missions.[17] Due to resource constraints and the complexity of conducting live, virtual, and constructive testing in a joint mission environment, JTEM is interested in determining if analytical techniques, like modeling and simulation, can be applied to understand the relationships between system-of-systems performance and joint mission effectiveness. As a proof of concept for investigating this possibility, the Network Enabled Weapon (NEW) was chosen as a framework for further study.

The NEW concept was born out of the requirement to create a network-centric integrated system. The scope of this research effort will be restricted to a test scenario for the current NEW concept of a sub 500-lb class, nonpowered, guided bomb with data link capabilities and several guidance modes intended to attack moving targets in adverse weather and high-threat environments from the launch platform.

As NEW systems are required to conduct more testing in the context of a joint mission, it will be essential that these tests be as efficient and useful as possible. With the complexity of the joint test environment, Modeling and Simulation (M&S) is one of

[16] Director, Operational T&E, Testing in a Joint Environment Roadmap Strategic Planning Guidance, United States Department of Defense, Final Report, November 2004, pp. 1-3.

[17] Eileen Bjorkman, Col, USAF, “JTEM Overview Briefing,” March 2006, slide 7.

the most effective tools to help understand the environment, design an efficient and useful test, and to help investigate robust possibilities in the use of forces to accomplish operational tasks.

This thesis will use an agent-based distillation, which is a type of computer simulation that is used to model the critical factors of interest without explicitly modeling all of the physical details. Chapter II provides a description of the operational system-of-systems construct and a discussion on model development. In Chapter III, the experimental design methodology will be introduced, along with a description of scenarios based on the NEW construct. These scenarios will be replicated in the simulation tool and then analyzed. The analysis process will use a technique called data farming. This involves using high-speed computing to run the simulations thousands of times, while simultaneously varying many input parameters. Using cutting edge experimental designs developed at the Naval Postgraduate School, the data resulting from these simulations will be analyzed and presented in Chapter IV in order to identify critical factors, interactions, and thresholds. The results of the statistical analysis will then be extended to conclusions in Chapter V about the operational context and used to support the development of a joint test plan for NEW operations. It is envisioned the results of this research will directly support the planning and operation of JTEM test events for NEW operations—beginning as early as summer, 2007.

II. SYSTEM DESCRIPTION AND MODEL DEVELOPMENT

> *The general who wins a battle makes many calculations in his temple before the battle is fought. The general who loses a battle makes but few calculations beforehand. Thus do many calculations lead to victory, and few calculations to defeat: how much more no calculation at all! It is by attention to this point that I can foresee who is likely to win or lose.*
>
> –Sun Tzu, *The Art of War*

A. CHALLENGES FOR TESTING IN A JOINT MISSION ENVIRONMENT

A unique challenge in assessing the effectiveness and suitability of systems in the joint environment is the multitude of possible interactions and outcomes in a system-of-systems construct. New and developing acquisition programs rely on interfaces with existing or future systems, quite possibly from separate services, to achieve mission success.

Focus on Joint Mission Effectiveness (JMe) has increased emphasis on joint and coalition forces, integrated operations, network-enabled warfare, capabilities-based planning, etc. Test and Evaluation (T&E) to ensure that systems can operate in this new environment thus becomes more important, and increasingly complex. A corollary requirement is the analysis of JMe to assist in test planning, to understand and quantify the contribution of individual systems to the accomplishment of that mission, and assess the degree to which the mission can be accomplished.

Within the Joint Mission Environment (JME), existing capability gaps impede successful execution of Joint Force Commander Joint Targeting Cycle processes against fixed, mobile, and relocatable planned and time-sensitive targets (TSTs). Flexible and responsive network operations across command, control, and communications systems, and intelligence, surveillance, and reconnaissance infrastructure are critical to successfully prosecuting these targets across multiple mission areas.

The concept of Precision Engagement typifies this system-of-systems approach that "enables our forces to locate the objective or target, provide responsive command and control, generate the desired effect, assess our level of success, and retain the flexibility to reengage with precision when required."[18]

B. NETWORK ENABLED WEAPONS (NEWs)

Unlike some other precision-guided munitions (PGMs), the emphasis behind NEWs is the ability to attack stationary and **mobile** targets within moments of their detection. The capability to engage moving targets is gained through use of an onboard seeker and post-release communications network, enabling the following attributes:

- **In-flight target updates and retargeting** provides target location update
- **Post-release communications acknowledgement** provides positive weapon control
- **Weapon in-flight status** provides feedback of weapon location and weapon status
- **Weapon abort** provides a weapon disabling feature
- **Bomb impact assessment** provides pre-impact target damage information[19]

NEWs achieves capability against mobile targets through updates from the launch aircraft or third-party targeting system via a weapon control network (WCN).

The base network configuration for this research will include three active nodes—the strike aircraft, the weapon, and the "weapon controller." The weapon controller can refer to either the strike (i.e., launch) aircraft or a third-party Joint Terminal Attack Controller (JTAC). A multitude of possible mission scenarios exist, but an example of a particular construct is provided in Figure 2. The lightning bolts represent networked communications between the entities involved. Through communications with the Combined Air Operations Center (CAOC), an identified target gets assigned to a mission

[18] Joint Chiefs of Staff, Joint Vision 2010, United States Department of Defense, Washington, D.C., 1997, p. 21.

[19] Headquarters, Air Combat Command, "Joint Enabling Concept for SDB II," Draft, p. 7-1, FOUO; not releasable to the public.

typical of the concept of operations for a NEW. During flight of the weapon, target location updates are passed to the guidance system of either the aircraft or the NEW in order to maneuver the munition to the target. This networked capability is what enables the engagement of moving targets without using existing technologies like laser-guided identification or camera-guided flight.

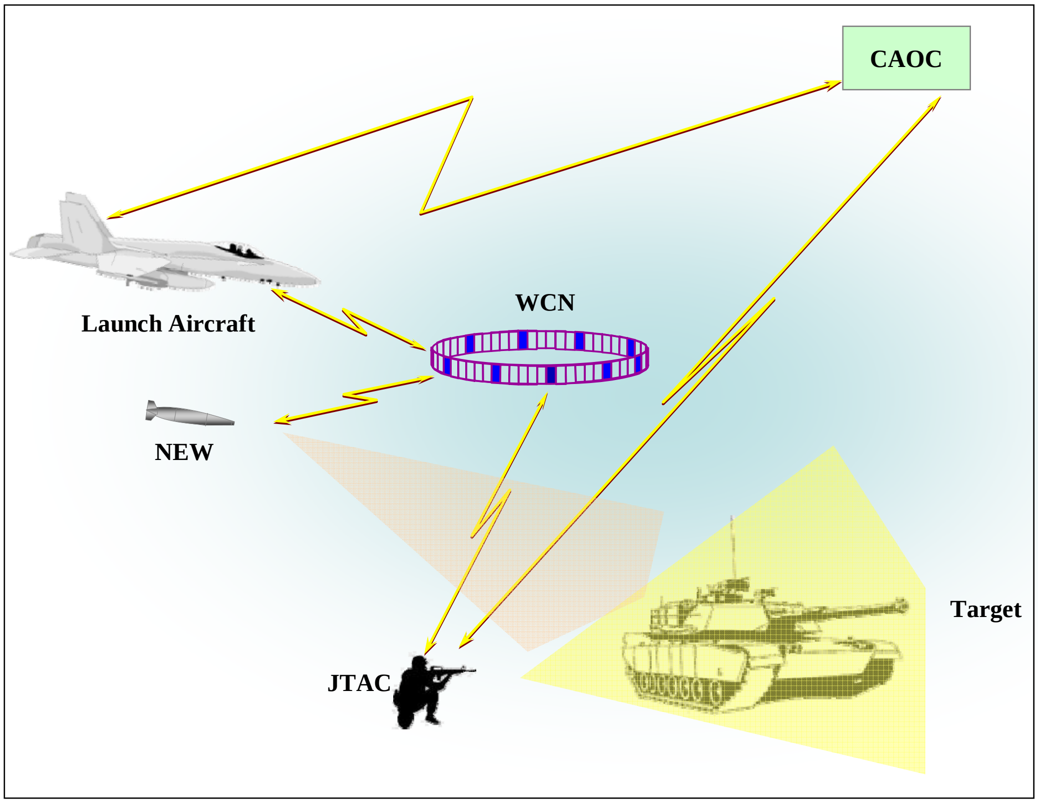

Figure 2. Guiding a NEW to the Target.

C. AGENT-BASED MODELING (ABM)

One approach towards gaining knowledge about the possible interactions associated with the NEW system-of-systems is through the application of ABM and Data Farming. ABM refers to a type of simulation made up of agents (or entities) that behave autonomously. These agents possess simple internal rule-sets for decision making, movement, and action. When combined with other entities in the model and subjected to stochastic conditions, the agents interact in ways that are often reflective of large-scale system behavior.[20] Data Farming involves the exploration of simulation models across a wide range of settings for the agents' characteristics and running the model a statistically significant number of times.[21]

In their report to JTEM, researchers for Referentia Systems, Inc.[22] described ABM and Data Farming:

> ABM can be viewed as a mathematical function; for a unique set of input (including any specific settings of the seeds for the random number generators used) there is only one output, both of which may be multidimensional. The goal of Data Farming is to understand that mapping, which may be very non-linear, to explore and identify the relationships between the input parameters and the output, to identify unexpected relationships, and to discover and characterize regions of the input space where discontinuities may exist.[23]

The overall objective for the use of Data Farming within JTEM is to extract as much information as possible from the models for each test scenario. It is envisioned that ABM will serve as a tool for refining the test space of possible parameters and parameter settings and narrow the focus for actual live test events.[24]

There have been significant amounts of research regarding the applicability of ABM in the military context.[25] As with many complex endeavors, military conflicts typify an environment of autonomous or semiautonomous agents, uncertainty in behavior and outcomes, a wide range of operational inputs, and complex interactions between

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[20] Susan M. Sanchez and Thomas W. Lucas, "Exploring the World of Agent-Based Simulations: Simple Models, Complex Analyses," Proceedings of the 2002 Winter Simulation Conference, December 2002, p. 1.

[21] Gary Horne and Ted Meyer, "Data Farming: Discovering Surprise," Proceedings of the 2004 Winter Simulation Conference, December 2004, p. 2.

[22] Researchers and analysts, widely regarded as pioneers in the application of ABM combined with Data Farming.

[23] Gary Horne, Steve Upton, and Lawton Clites, Joint Test and Evaluation Data Farming Project: Initial Feasibility and Framing, Final Report under Contract N00164-05-D-6656 TO 005, 31 January 2007, p. 15.

[24] Ibid., p. 24.

[25] See Recent Theses and Papers at http://harvest.nps.edu; last accessed in April 2007.

entities.[26] ABM offers an exploratory analytical approach to broadly consider uncertainties associated with elements of warfare that might otherwise be too costly or time intensive to study with other means.

D. MODEL DEVELOPMENT

Under a research contract sponsored by JTEM, Referentia Systems, Inc. developed an ABM for the system-of-systems concept. Built in the MASON programming language[27] and dubbed "TheTester," the model contains the functionality desired for studying the complex interactions within a NEW scenario. In close coordination with JTEM and the program offices responsible for networked weapons, the author and the model developer worked through numerous iterations of programming and debugging over the course of six months in order to refine the model and improve its performance. Due to the speed of the model runs, and the graphical user interface implemented by the developer, the author was able to provide timely feedback and corrective suggestions to fix output anomalies. The types of agents contained in the final model used in this research effort include:[28]

- Mobile and stationary targets of various classifications
- Strike aircraft
- NEWs
- JTAC—ground-based and analogous Unmanned Aerial Vehicle (UAV)
- WCN
- Command and Control (C2) Center[29]

At the start of the simulation, stationary, mobile, or pop-up targets are placed on a three-dimensional grid through use of an input file. When a target enters the sensor range of a JTAC agent, a stochastically governed detection may occur. Upon detection, the

[26] Thomas Cioppa, Thomas W. Lucas, and Susan M. Sanchez, "Military Applications of Agent-Based Simulations," Proceedings of the 2004 Winter Simulation Conference, December 2004, p. 1.

[27] See http://www.cs.gmu.edu/~eclab/projects/mason/; last accessed in April 2007.

[28] Each of these agents and their parameters are explained in further detail in Chapter III.

[29] Gary Horne, Steve Upton, and Lawton Clites, Joint Test and Evaluation Data Farming Project: Initial Feasibility and Framing, Final Report under Contract N00164-05-D-6656 TO 005, 31 January 2007, p. 11.

JTAC relays a close air support (CAS) request through the C2 network to an available strike aircraft. The aircraft proceeds toward the target coordinates given by the JTAC until it reaches a predetermined launch (i.e., stand-off) distance. During flight, the strike aircraft receives target location updates directly from the JTAC.

When the strike aircraft reaches the launch distance, the NEW is released if the target location information is not "stale." If this condition is not satisfied, the strike aircraft either returns to base or remains on course toward the last known target position and, after a set interval, attempts another launch.

Upon successful launch of the weapon, the NEW receives in-flight target updates (IFTU) of the target's location until it gets within internal sensor range of the target. At that point, the weapon proceeds autonomously towards the target, in accordance with the rule set for its parameter settings. At any point during the pre- or post-launch sequence, if a target of higher "value" (HVT) is sensed by the JTAC, then the HVT becomes the target of primary interest. If post-launch, the JTAC will query the NEW through the WCN to determine if it has the capability to reach the HVT. If it does, then the NEW will redirect its course and attempt to destroy the HVT. Otherwise, the NEW proceeds toward the original target. In either case, once the NEW goes into autonomous seeker mode, the JTAC is no longer required to provide IFTUs, and therefore continues sensing for new targets—possibly including the original target in the case of a redirect.

The main indicator of whether the engagement achieved the desired JMe centers on the concept of probability of a single-shot-kill. In other words, was the best available target destroyed in a timely manner with a single NEW? As will be explained in the next chapter, there are numerous dynamics affecting the outcome for each set of factor settings. The goal will be to determine which of those factors (and factor settings) most influences "success" of the mission in the model. From a thorough examination of the interactions within this joint system-of-systems model, it will be possible to draw recommendations regarding the best approach for live testing of a NEW mission—thereby achieving JTEM's objectives for this research.

Chapter III provides the foundation for the experimental design, as well as a detailed description of the model agents, their individual parameters, and the ranges over which the parameters are varied. It concludes with a discussion of the model output (i.e., measures of effectiveness) and how that output will be used to address the key research objectives for this thesis.

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III. DESIGN OF EXPERIMENTS (DOE)

The secret of all victory lies in the organization of the non-obvious.

–Marcus Aurelius

Marcus Aurelius, Emperor of the Roman Empire from 161-180 A.D., was considered one of the great Stoic philosophers.[30] The Stoic mindset of “following where reason leads” typifies the leadership expressed in his quote above, for it is through an investigation of the potential nonobvious outcomes of decisions that allow informed leaders to improve their likelihood of success.

Leaders in the Department of Defense (DoD) routinely make decisions involving expenditures of billions of dollars or involving life and death situations for personnel under their command. In an ideal setting, the outcomes of those decisions would be known with certainty. In reality, however, the vast number of factors with influence on the process or system under consideration often introduces a high degree of uncertainty in the outcome. To reduce the uncertainty, DoD authorities rely on experimentation to help understand the potential impacts of their decisions. Modeling and Simulation (M&S) is commonly used to replace live experimentation when real world systems are unavailable or, as is often the case, too expensive to devote to testing.[31]

A. GENERAL APPROACH

Rather than taking a “trial and error” approach to experimental design (be it live or in the M&S environment), researchers often utilize specialized techniques to organize the myriad of possible parameter settings. The overall objective of the design is to maximize the information gained from a limited number of experimental runs.

[30] For more on Marcus Arelius and Stoic philosophy see http://en.wikipedia.org/wiki/Marcus_Aurelius and http://en.wikipedia.org/wiki/Stoicism, respectively. Last accessed in May 2007.

[31] Thomas W. Lucas and Susan M. Sanchez, “The Brave New World of Simulation Experiments for Defense and Homeland Security Applications,” Proceedings of the 2006 Joint Statistical Meetings, p. 1.

In his Ph.D. Dissertation at the Naval Postgraduate School, LTC Thomas Cioppa, USA, provides an approach to experimentation geared toward addressing the issue of efficient design and analysis techniques for complex simulation models. His research indicates that the use of orthogonal, or nearly orthogonal, Latin hypercubes with excellent space-filling properties enable efficient exploration of simulation models.[32] Unlike traditional factorial designs, which test only a few factors at a minimum number of levels, a space-filling design explores a broad landscape of factor settings. The orthogonality of the design improves the analysis of model results by decreasing dependence among regression coefficient estimates, and by allowing investigation of multiple high-order interactions, nonlinear relationships, and discontinuities in the response.[33]

Figure 3 demonstrates the space-filling properties of the Nearly-Orthogonal Latin Hypercube (NOLH) design. The figure displays the pairwise combinations of factor settings in a two-dimensional projection. For example, the highlighted block shows the combination of factor settings this experiment would test for Factor B and Factor D. In three dimensions, the image would portray settings for three factors spaced efficiently throughout a cube. While we cannot visually comprehend the image in seven dimensions, the mathematics and the concepts still hold true. For seven factors, this design approach allows the exploration of model effects across 17 uniformly distributed factor settings, in a total of as few as 17 model runs. In comparison, a three-level, full factorial design of seven factors would require 37, or 2,187 model runs, and would only examine three levels of each factor. Considering that the intent is to replicate each design point hundreds or thousands of times to draw out the true nature of the stochastic response, the orders of magnitude difference in the number of model runs becomes increasingly significant. More poignantly, when considering that this research will examine the effects and interactions of more than 20 factors in each design, the significance is the difference between running 100 replications on a single laptop

[32] Thomas M. Cioppa, LTC, USA, “Efficient Nearly Orthogonal and Space-Filling Experimental Designs for High-Dimensional Complex Models,” Ph.D. Dissertation, Naval Postgraduate School, Monterey, CA, September 2002, p. 9.

[33] Ibid., p. 21.

computer in five hours, or waiting until the sun burns out (e.g., 2017 x 100 runs) and never seeing the results—and this is for a simulation model that takes less than one second to complete each run.

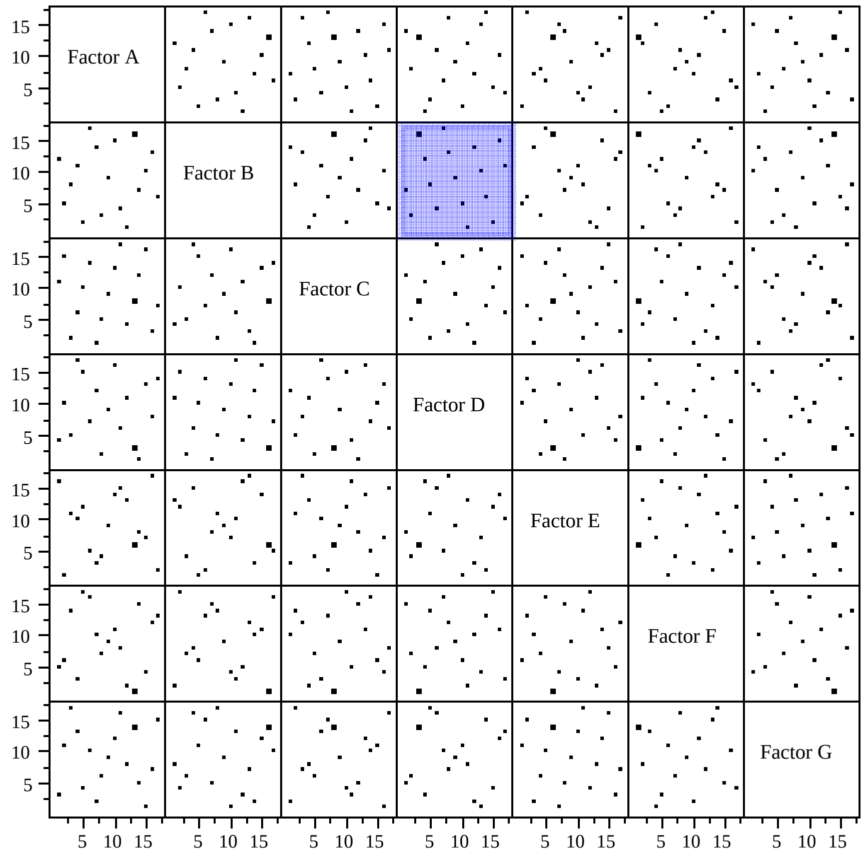

Figure 3. NOLH Scatterplot for 7 Factors and 17 Design Points Demonstrating Excellent Space-Filling Properties of the Design.

B. MODEL PARAMETERS

Each of the agents described in Chapter II possess one or more characteristics that define their behavior within the model. Depending on the specific scenario and the objectives for each design, some of the characteristics (synonymously referred to as parameters or factors) will be held to a constant value, while the majority are varied over a predefined range. Unless specifically stated otherwise, the factors are set to a particular value for each model run and do not fluctuate during that particular run. The following sections describe the parameters for each agent. A summary description is provided in Appendix A.

1. Joint Terminal Attack Controller (JTAC)

The JTAC is typically a ground-based controller deployed within the immediate vicinity of potential or known targets. He possesses sensor capabilities, communication devices, and equipment necessary to locate, identify, and track targets. Additionally, he is able to relay target location information to other agents on the Weapon Control Network (WCN). The agent could be used to replicate an air-based controller, such as an Unmanned Aerial Vehicle (UAV), by adjusting the parameters according to the characteristics of the entity being modeled.

a. Speed

If necessary, the JTAC can be assigned waypoints from his initial location to traverse during execution of the scenario. The *speed* setting controls how fast the JTAC moves between the assigned waypoints. Speed is measured in meters/second.

b. Sensor Range

The JTAC *sensor range* is a radial distance defining a circular representation of the agent's ability to identify and track targets. The sensor characteristics are commonly referred to as "cookie cutter," indicating a defined probability of detection for targets within range and a probability of zero for targets outside the range. Sensor range is measured in meters.

c. Probability of Detection (Pd)

Targets within the JTAC's sensor range are detected according to the assigned *Pd*. During each model time step, a random draw determines whether or not the target is detected. The logic within the model can be adjusted such that the Pd becomes one (certainty), after initial detection occurs, to simulate focused attention on the target.

d. Multi-Target Degradation Factor (MTDF)

In scenarios containing more than one target, the JTAC's ability to detect multiple targets may be degraded to represent the difficulty associated with simultaneous engagements. The *MTDF* is a factor between 0 and 1 applied multiplicatively to the Pd.

e. Target Location Error (TLE)

TLE defines the accuracy associated with the JTAC's perception of the true location of the target. It is represented in the model by a Bivariate Normal distribution and is defined by two parameters, the mean and standard deviation.[34]

f. In-Flight Target Update (IFTU) Interval

The JTAC does not continuously provide target location updates to other agents on the network. Instead, updates are transmitted at a frequency defined by the assigned *IFTU*—measured in seconds.

2. Network Enabled Weapon (NEW)

The NEW for this study is a nonpowered weapon launched from an aircraft. The combination of networked communications, control surfaces, and internal guidance systems give it the ability to redirect its path during flight and engage moving targets. Upon direction of the JTAC, the NEW is also capable of being reassigned to a higher-value target (HVT) during flight. Rather than modeling the complicated physics associated with determining a nonpowered weapon's ability to reach a new target, a simplified approach was developed. Upon request from the JTAC for a redirect, the model calculates the three-dimensional slant distance to both targets and adjusts the weapon's path only if the HVT is closer than the original target. In the case where the

[34] Jay L. Devore, Probability and Statistics for Engineering and the Sciences, 6th Edition, 2004, Thomson Brooks/Cole Publishers, 2004, p. 543.

weapon is not able to reach the HVT, a message is transmitted through the network to the JTAC indicating the redirect was denied, and the NEW continues flying toward the original target.

a. Speed

The true speed of flight is, again, a complicated physical process to model. The simplifying approach for this study is to vary the *speed* as a parameter across a typical range between maximum glide performance and minimum time to target. Every effort was made to consult with Subject Matter Experts (SMEs) in order to accurately represent weapon performance.[35] Speed is measured in meters/second.

b. Impact Radius

The *impact radius* defines a circular area of lethality around the center of the bomb's impact location. Upon impact, the model determines whether the target's true location is within the area and, in combination with the probability of kill (Pk), assigns a target kill or miss accordingly. The impact radius is measured in meters.

c. Sensor Range

The *sensor range* identifies the point at which the NEW acquires autonomous recognition of the target. The performance within the model is similar to the "cookie cutter" approach described for the JTAC agent. Once the NEW is within this three-dimensional range to the target, it no longer receives IFTUs through the network; instead relying on its own sensor characteristics to guide it to the target.

d. Target Location Error

The *TLE* is identical to the process described for the JTAC. The Gaussian mean and standard deviation parameters, however, will take on a different range of values in order to more closely represent NEW sensor capabilities.

[35] The author and model developer consulted in person with SMEs from Joint Command and Control for NEW and SDB II program offices, Eglin AFB, on 26 April 2007.

e. Probability of Detection (Pd)

Once in autonomous seeker mode, the NEW relies on its own *Pd* to determine if it senses the target during a particular time step. Unlike the JTAC, however, the Pd is always a random draw, according to the parameter setting.

f. Probability of Kill (Pk)

Combined with the impact radius, the NEW's *Pk* value determines whether or not a target is killed. The Pk is limited to very high (i.e., favorable) values to replicate the likelihood of correct weapon detonation upon impact.

3. Target

Targets for this study are notional in that they do not have any distinguishing characteristics to differentiate them among typical NEW target sets. Targets can, however, be assigned a priority value in order to account for the presence of an HVT. Also, the targets may be assigned different Pd and Pk values for the JTAC and the NEW. The two parameters explicitly varied as part of the DoE are the target speed and the pop-up time.

a. Speed

For each scenario, the target(s) are assigned predetermined waypoints to traverse. The target may be set to cycle through the waypoints continuously or stop when it reaches the last one. The target *speed* is used to differentiate between categories of targets. For example, vehicular targets typically travel at much greater speeds than dismounted (i.e., foot patrol) targets. Speed is measured in meters/second.

b. Pop-Up Time

Each target in the scenario may be designated a particular time step in which it first appears. The *pop-up time* presents the opportunity to investigate system effectiveness against a HVT that may result in a redirecting a NEW already in flight.

4. Launch Aircraft

The aircraft's initial location can be varied within the model, but for the purposes of this study, the starting position is simulated as a Combat Air Patrol (CAP) orbit approximately 100 kilometers (km) south of the JTAC at an altitude of six km. After target identification, the aircraft agent receives an assigned mission from the Command and Control (C2) Center and is loaded with a predetermined number of NEWs. The aircraft is then directed toward the target by location updates relayed directly from the JTAC. In accordance with the parameter settings for a particular model run, the aircraft attempts to launch the NEW and then proceeds back to its starting position. The aircraft may, if equipped with remaining weapons, be directed at any point to conduct another mission.

a. Speed

The aircraft *speed* setting is varied over a range representative of a typical strike aircraft and is constant throughout a particular model run. Aircraft speed is measured in meters/second.

b. Launch Distance, Update Requirement, Number of Attempts, and Reattempt Interval

This section describes four different factors for the aircraft agent. The *launch distance* represents the stand-off distance where the aircraft will initially attempt to release the NEW. If the target location information has not been successfully relayed to the aircraft within the time period set by the *update requirement* factor, the aircraft will not launch the weapon. This is designed to limit the launch of a weapon when the target is no longer within sensor range of the JTAC. Based on the *number of attempts* setting, the aircraft may make subsequent attempts to launch the NEW, at a frequency governed by the *reattempt interval*. While awaiting multiple attempts to launch the weapon, the aircraft continues to fly toward the last known target location.

5. Weapon Control Network (WCN)

The WCN is the host for the flow of communication between the NEW and JTAC agents. It is the heart of the capability to operate in a network-centric environment. While there are a multitude of potential issues and limitations affecting the transmission capability and interoperability of systems across any network, the model used for this research considers only two of the important factors. The range of the network is simulated to encompass the entire range of the battlespace.

a. Reliability

The *reliability* of the network is a parameter that governs the random probability of a successful message transmission. For the purposes of this research, messages transmitted are either fully received or not at all—there are no instances of partial (or garbled) communications.

b. Latency

Latency is a measure of how long it takes for a message to be transmitted across the network and is measured in seconds.

6. Command and Control (C2) Center

When the JTAC senses a target, the information is transmitted to the C2 Center in the form of a Close Air Support (CAS) request. The intent is to simulate a command element within the scenario with the authority to assign an aircraft equipped with a NEW to prosecute the target.

a. Decision Time

The only parameter currently in use for the C2 agent is the latency associated with the amount of *decision time* it takes to assign the mission to an available aircraft. The time is measured in seconds and effectively introduces a delay in between target identification and CAS mission authorization.

C. SCENARIO DEVELOPMENT

NEW missions typically fall into the category of “reactionary strike,” meaning targets of opportunity that involve little or no prior knowledge of the target’s exact location and/or route. The missions may involve moving or stationary targets.

This research considers a scenario involving ground-based mobile targets and a JTAC as the post-launch weapon controller. One of the targets is envisioned as a wheeled vehicle that follows a prescribed route within the vicinity of the stationary JTAC. Depending on the settings for a particular model run, a second target of higher priority, simulating a dismounted combatant may “pop up” in the battlespace.

As depicted in Figure 4, the JTAC is located at the center of the simulation battlespace. The vehicular target begins its route at a position 2,000 meters east and 1,000 meters north of the JTAC. The target then follows a series of set waypoints at its designated speed. At some point in the scenario, the target will enter (and exit if not destroyed) the sensor range of the controller, initiating a CAS request once detected. In some scenarios, an HVT may appear to the southeast of the controller’s position. This target will cycle through a square pattern at a speed indicative of a human on foot patrol. Upon detection of the HVT, the JTAC will submit a new CAS request, which may result in either an attempt to redirect an inbound NEW or the launch of a second weapon, if available.

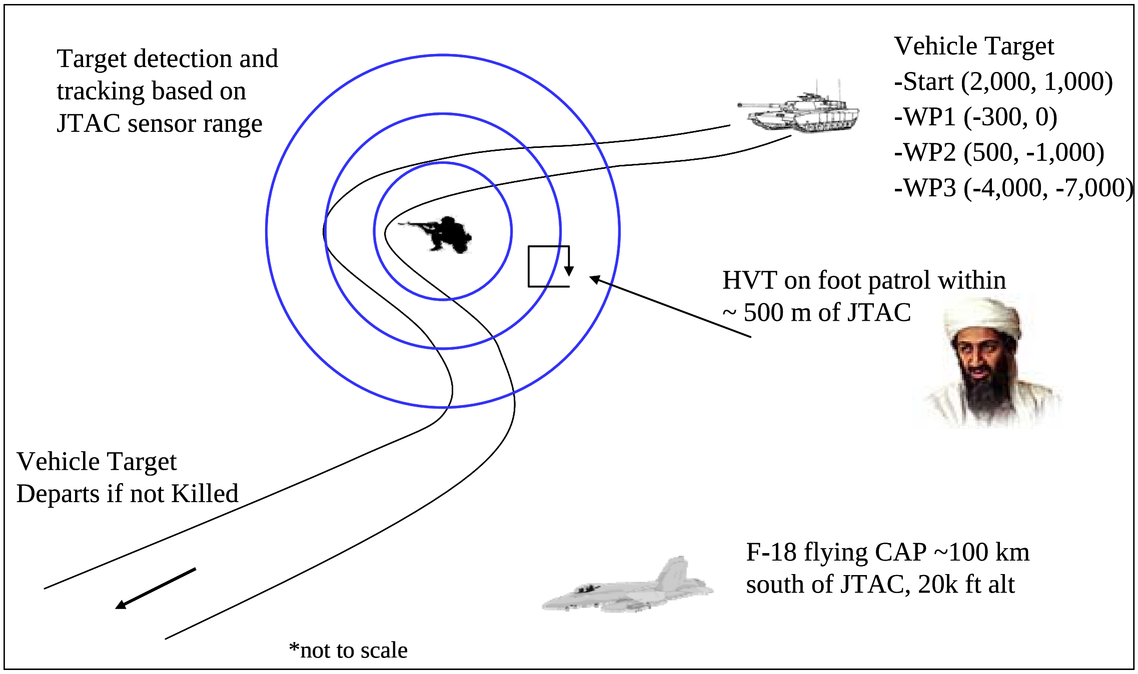

Figure 4. Visual Depiction of the Battlespace Indicating JTAC Positioning and Target Routing.

This scenario is based, in part, on mission descriptions found in the draft Joint Enabling Concept document for SDB II.[36] The intent is to simulate a realistic operational setting that would offer the opportunity to test the NEW system-of-systems' effectiveness against mobile targets and time-sensitive HVTs. Several effectiveness measures were developed in order to facilitate the assessment.

D. MEASURES OF EFFECTIVENESS (MOEs)

Because of resource constraints and the complexity of conducting testing in a joint mission environment, JTEM is interested in determining if analytical techniques, like modeling and simulation, can be applied to understand the relationship between system-of-systems performance and Joint Mission Effectiveness (JMe). Specifically, this research was designed to address the following questions:

[36] Headquarters, Air Combat Command, "Joint Enabling Concept for SDB II," Draft, Section 8, FOUO; not releasable to the public.

- For a particular scenario, what are the potential performance parameters (and their applicable ranges) requiring testing to determine system capability?
- Given that the ability to conduct live testing is resource constrained, what is the critical collection of parameter inputs to test?
- For a particular construct, are there possible mixtures of operational forces or Tactics, Techniques, and Procedures (TTPs) that could have a significant impact on JMe?
- Can Agent-Based Modeling (ABM) assist JTEM in determining approaches to Joint Test and Evaluation?

The main measure used in this study to address the research questions is the number of target kills. The output files generated by the model provide a binary description of whether a particular model run resulted in a kill for each target type, as applicable. The pertinent output data generated by the model is presented in Table 1.

MOE	Description
Target Kill	Binary kill indicator for each target type in each model run
CAS Requests	Total number of CAS requests in each model run
NEW Launches	Total number of NEW launches in each model run
Abort – No Target Update	Mission abort – Launch aircraft did not have recent target info
Redirected	Redirect of the NEW occurred during mission
Redirect Denied	Redirect of the NEW denied during the mission
Hit – No Kill	NEW hit within impact radius of target, but no kill
Outside Impact	NEW missed the target

Table 1. Model Output Used as MOEs.

E. EXPERIMENTAL DESIGNS

The designs used for the research are based on the orthogonal and space-filling concepts previously discussed. Two NOLH design matrices[37] were constructed—one for a scenario involving the vehicular target and one containing parameters for both the vehicular and pop-up HVT. Table 2 shows the parameter settings for the two target

[37] The spreadsheet tool used to build the designs can be found under the Software Downloads link at http://harvest.nps.edu.; last accessed in April 2007.

scenario. A total of 27 factors were varied over the ranges shown. Several factors, such as the pop-up time for the Mobile-1 target, are included in the table but were assigned a specific value consistent across all model runs. The one target scenario factor ranges are identical to those shown in Table 2, with the exception of the six highlighted parameters unique to the HVT scenario, which were excluded.

Factor Name	Description	Low Value	High Value	Units
Tgt_A_Spd	High-Value Target (HVT) Speed	0.5	4	meters/sec
Tgt_A_PUT	HVT Pop-up Time	100	600	seconds
Tgt_C_Spd	Vehicular Target Speed	4	20	meters/sec
Tgt_C_PUT	Vehicular Target Pop-up Time	10	10	seconds
NEW_Spd	NEW Speed	140	200	meters/sec
NEW_ImpRad	NEW Impact Radius	3	30	meters
NEW_SnsrRng	NEW Sensor Range	1000	3000	meters
NEW_TLEmu	NEW Mean Target Location Error (TLE)	0	5	meters
NEW_TLEsigma	NEW TLE Standard Deviation	0	2	meters
NEW_PdA	NEW Probability Detect HVT	0.85	1.0	n/a
NEW_PdC	NEW Probability Detect Vehicular Target	0.85	1.0	n/a
NEW_PkA	NEW Probability Kill HVT	0.9	1.0	n/a
NEW_PkC	NEW Probability Kill Vehicular Target	0.9	1.0	n/a
AC_Spd	Aircraft Speed	154	254	meters/sec
AC_LnchDist	Aircraft Stand-off Launch Distance	18.5	74	kilometers
AC_UpdtReq	Aircraft Requirement for Target Info Recency	10	45	seconds
AC_LnchAtmpts	Aircraft Number of Launch Attempts	1	5	n/a
AC_LnchIntrvl	Aircraft Interval Between Launch Attempts	10	30	seconds
JTAC_Spd	JTAC Speed	0	0	meters/sec
JTAC_SnsrRng	JTAC Sensor Range	500	5000	meters
JTAC_MTDF	JTAC Multi-Target Degradation Factor	0.5	1.0	n/a
JTAC_TLEmu	JTAC Mean TLE	10	100	meters
JTAC_TLEsigma	JTAC TLE Standard Deviation	2	20	meters
JTAC_PdA	JTAC Probability Detect HVT	0.7	1.0	n/a
JTAC_PdC	JTAC Probability Detect Vehicular Target	0.7	1.0	n/a
JTAC_IFTU_Intrvl	JTAC In-flight Target Update Interval	15	60	secnds
WCN_Rel	Weapon Control Network Reliability	0.95	1.0	n/a
WCN_Lat	Weapon Control Network Latency	0	3	seconds
C2_DecTime	Command and Control Decision Time	10	200	seconds
	Indicates factors not used in the one target scenario			

Table 2. Factor Settings and Ranges for the Two-Target Scenario.

Figure 5 shows a two-dimensional projection for eight of the factor combinations in the single target (21-factor) design. As previously shown in the example at Figure 3, the design exhibits outstanding space-filling properties.

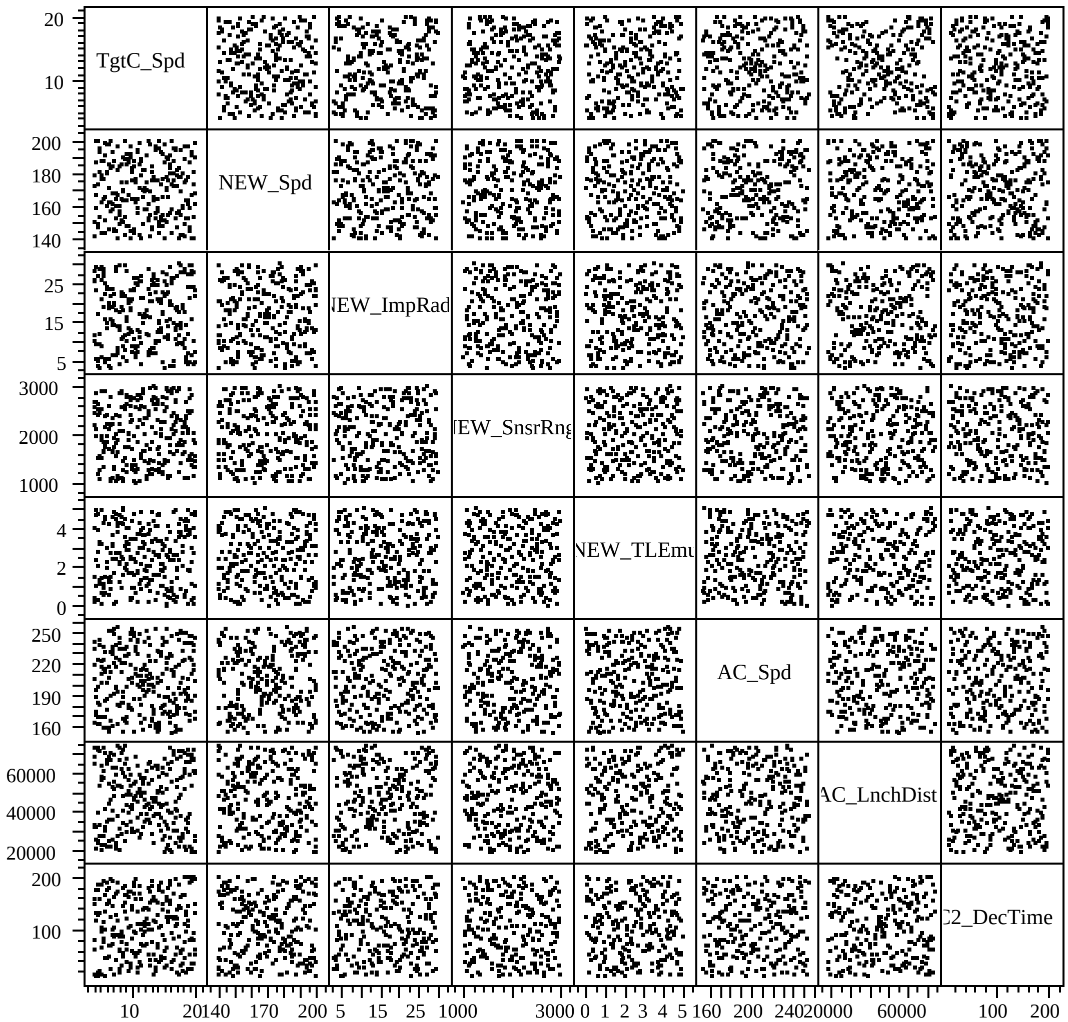

Figure 5. Scatterplot Matrix for a Selection of Eight Factors Exhibiting Excellent Space-Filling Properties of the Design.

Table 3 shows the shows the correlation matrix for the same eight factors. As indicated in Cioppa's research, the columns of the design matrix are "nearly orthogonal," exhibited by the minimal correlation, in this case much less than +/– 0.03.[38] The decision to display a selection of only 8 of the 21 factors included in the design was one of presentation and space. The concept and the design results extend similarly to an analysis of the complete experimental design matrix.

38 Thomas M. Cioppa, LTC, USA, "Efficient Nearly Orthogonal and Space-Filling Experimental Designs for High-Dimensional Complex Models," Ph.D. Dissertation, Naval Postgraduate School, Monterey, CA, September 2002, p. 23.

Correlations								
	TgtC_Spd	NEW_Spd	NEW_ImpRad	NEW_SnsrRng	NEW_TLEmu	AC_Spd	AC_LnchDist	C2_DecTime
TgtC_Spd	1.0000	-0.0004	0.0003	0.0000	0.0000	-0.0002	0.0019	-0.0001
NEW_Spd	-0.0004	1.0000	0.0018	0.0017	0.0018	-0.0001	0.0005	-0.0006
NEW_ImpRad	0.0003	0.0018	1.0000	-0.0002	0.0005	0.0002	0.0005	-0.0003
NEW_SnsrRng	0.0000	0.0017	-0.0002	1.0000	0.0000	0.0013	-0.0003	0.0005
NEW_TLEmu	0.0000	0.0018	0.0005	0.0000	1.0000	0.0009	0.0011	0.0005
AC_Spd	-0.0002	-0.0001	0.0002	0.0013	0.0009	1.0000	-0.0011	-0.0009
AC_LnchDist	0.0019	0.0005	0.0005	-0.0003	0.0011	-0.0011	1.0000	-0.0010
C2_DecTime	-0.0001	-0.0006	-0.0003	0.0005	0.0005	-0.0009	-0.0010	1.0000

Table 3. Pairwise Correlation Matrix Indicating Minimal Correlation Among the Columns of the Design.

The NOLH approach used in this research created 257 unique design points, or excursions. Each excursion was replicated 100 times, for a total of 25,700 simulated tests for each scenario. Chapter IV follows with a discussion of the results and an explanation of the analytical tools used to process the simulation output data.

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IV. RESULTS – DATA ANALYSIS

The purpose of computing is insight, not numbers.

–Richard Hamming

This chapter covers the analysis conducted to address the research questions. It is important to note that the intent of the design and analysis approach in this thesis was to stress the system-of-systems concept in ways that may not have been intended by the architects of specific entities within the construct. Specifically, while every attempt was made by the author to represent realistic characteristics of a Network Enabled Weapon (NEW), the overall objective was not to prove or demonstrate a certain level of capability. Rather, the intent was to gain insight into system performance from the standpoint of which factors (and at what settings) most significantly affects overall system behavior. Review of the results and analysis from this research must be kept in context with the description of the model and the scenarios, as previously discussed. Extrapolation of the results beyond the particular parameter settings used in the designs is discouraged—investigation into that realm remains a topic for future study.

A. STATISTICAL SETUP

Analysis of the model output was conducted with JMP Statistical Discovery Software, Version 5.1. JMP is a division of SAS, a leader in business intelligence and analysis, and is an accepted standard worldwide in the research, educational, and business fields.[39] This section describes the procedures used to extract the model output into useful files for analysis. Also covered in this section is a general introduction to the statistical methods used to interpret the results.

[39] See http://www.jmpin.com.; last accessed in May 2007.

1. Procedures for Extracting and Summarizing Model Output

Each run of the model generated an output data file that contained the results of the Measures of Effectiveness (MOEs) discussed in Chapter III. In order to equate the output to the corresponding input variables for a specific design point, a Ruby[40] script was written that matched the design matrix to the output and created a single comma separated value file.[41] Each row of the output.csv file contains an organized sequence of values for the input parameters, followed by the specific MOE values generated by the model as the response. In the case of an experiment consisting of 257 design points (DPs) and 100 replications, the output.csv file would contain 25,700 rows.

Once the output was organized into an acceptable format, the data was imported into JMP for further analysis. The first technique involved combining the data into summary statistics. Since the same inputs were used in each replication of a specific DP, the use of the mean value of the MOE across all replications (in this case, 100) serves as a "sufficient statistic" and reduces the variance within a set of inputs while preserving all of the information regarding the true nature of the response.[42]

2. Brief Explanation of Stepwise Regression and Partitioning Trees

The two main tools used in this research to analyze the results are Stepwise Regression and Partitioning Trees. The theory behind each method is addressed here briefly, while the specific application of the approach is covered in more detail in the following sections, as results are presented.

Regression analysis deals with the stochastic relationship between predictor variable(s) (also referred to as explanatory or independent variables), and at least one response variable of interest. The procedure is useful for making inferences about the effects changes to the inputs have on the output and provide a quantitative measure of the

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[40] See http://ruby-lang.org/en.; last accessed in May 2007.

[41] Files listed with a .csv extension refer to comma separated value format.

[42] V.K. Rohatgi, An Introduction to Probability Theory and Mathematical Statistics, John Wiley and Sons, Inc., June 1976, pp. 339-340.

extent of those effects.[43] In JMP, Stepwise Regression is a selection within the model-fitting platform and is an approach to selecting a subset of effects for a regression model. It is often used when there is little theory to guide the selection of terms for a model, but the modeler believes the approach will provide a good fit. The approach has been used practically, however, for over 30 years to help reduce the size of models and predict many kinds of responses, including nonlinear interactions.[44]

Partitioning Trees provide a method to separate the predictor variables into sets of data that explain significant differences in the response. To perform each "split" of the tree, the statistical software recursively divides the factor which most significantly separates the means (in the case of continuous variables) by examining the differences in sums of squares. The method is often very useful, especially with large data sets, because there are no prior assumptions required regarding the underlying distribution of the response and, as will be shown, analysis of the results is very straightforward.[45]

B. RESULTS FOR THE ONE TARGET SCENARIO

The first experiment involved the examination of NEW system effectiveness for the case of one mobile target, a ground-based weapon controller, and an aircraft equipped with one NEW. The Design of Experiments (DoE) included 21 factors, 257 DPs, and 100 replications of each DP. The complete DoE is provided in Appendix B.

Figure 6 provides the initial split of a partition tree with proportion of target kills as the MOE. The top block indicates an overall 0.48 kill rate for all 257 DPs.46 Increases in the proportion of target kills are considered an improvement in the response—shown as branching to the right for this particular tree. As the figure indicates, the most critical factor in the model for determining kill rate is the target's speed. For the 147 DPs with target speed set less than 13.19 m/s (approximately 29.5

[43] Jay L. Devore, Probability and Statistics for Engineering and the Sciences, 6th Edition, 2004, Thomson Brooks/Cole Publishers, 2004, pp. 497-498.

[44] JMP User's Guide, Companion Software to JMP 5.1, 2003.

[45] Ibid.

[46] The number of data points in each block will be shown by "Count" on the partition tree.

mph), the model indicates an improvement in target kills to 74%, opposed to approximately 14% for the other 110 cases. Successive splits of the partitioning tree occur sequentially for the parameter explaining the most variation in the response.

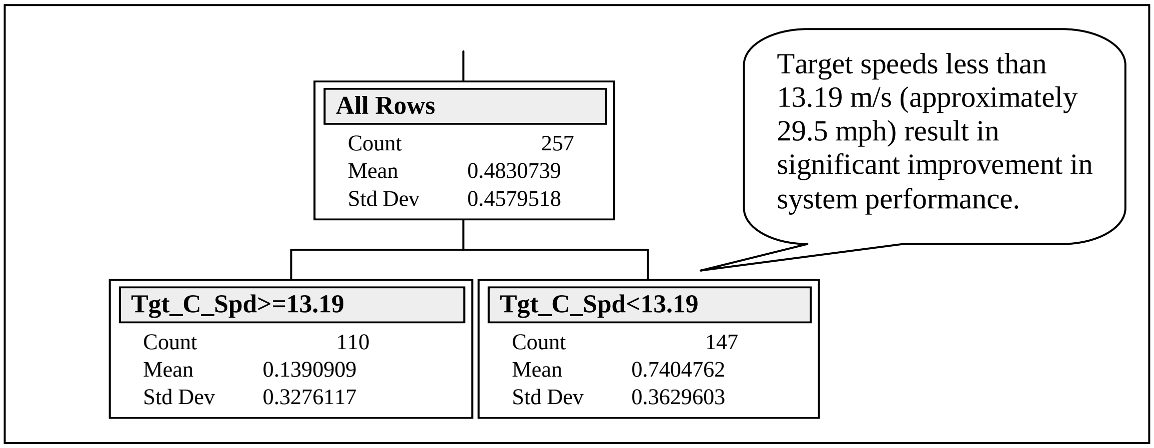


Figure 6. First Split of a Partition Tree for Target Kills as the MOE.

The results shown in Figure 7 provide a more complete breakout of the factors impacting target kills. As previously mentioned, interpretation of the splits for this MOE is that branching to the right indicates an improvement in the response. Each box should also be viewed as conditional upon the parameter value(s) in the preceding levels of the tree. For example, the block in the bottom right corner of the tree contains 98 DPs where the JTAC sensor range is greater than or equal to 2117 meters and greater than or equal to 1150 meters (which is trivial in this case), and where target speed is less than 13.19 m/s.

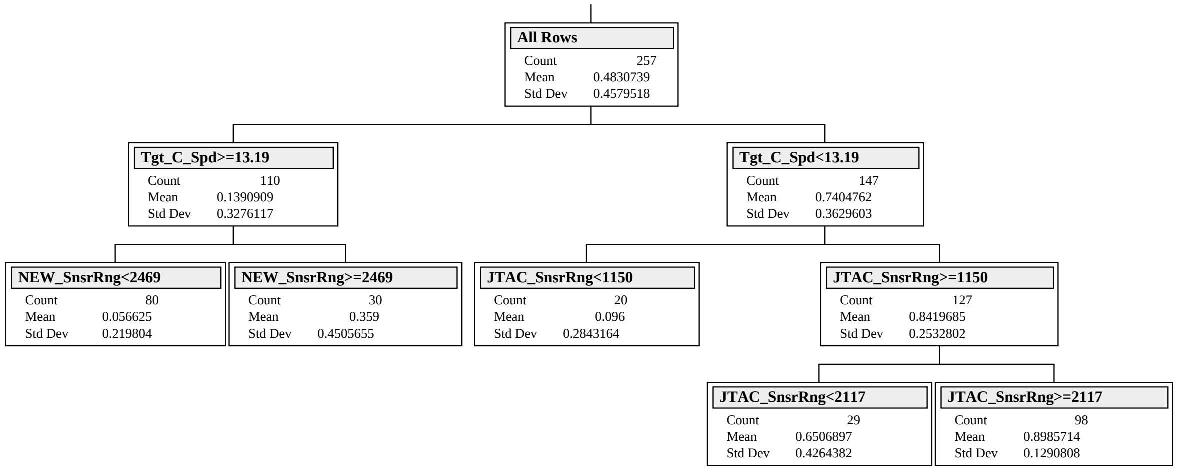


Figure 7. First Five Splits of the Partition Tree for Target Kills as the MOE.[47]

Two important points are revealed in Figure 7. First, if the operational context includes targets traveling greater than the threshold speed of 29.5 mph, then the model indicates improvements in NEW system performance may still be achieved if the weapon's internal sensor range is greater than approximately 2,500 meters. Secondly, for targets with speeds less than 29.5 mph, an increase in the JTAC's sensor range beyond approximately 2.1 kilometers may result in an overall 80% improvement in target kills—shown by comparing an MOE value of ~0.90 in the lower right branch to the 0.48 value at the root node. The apparent significant impact of the time/distance relationships exhibited by the results warrants further exploration.

Regression analysis was used to further investigate the parameters affecting the simulation model's response of target kills. The first approach considered the main effects only—meaning only the factors themselves, without consideration of second order interactions and quadratics, were included in the analysis. Figure 8 shows the Stepwise Regression control panel within JMP. The figure is used to illustrate the settings chosen for the regression model. The user selects a probability to enter the model and a probability to leave. These levels indicate the statistical significance a potential regressor term must achieve for it to be considered in the model in a forward or

[47] Successive splits on the same parameter is often an indicator of a nonlinear effect.

backward step, respectively. The direction can either be specified as forward, backward, or mixed. The mixed setting was used to cause the process to alternate between forward (adding terms) and backward (removing terms) steps.

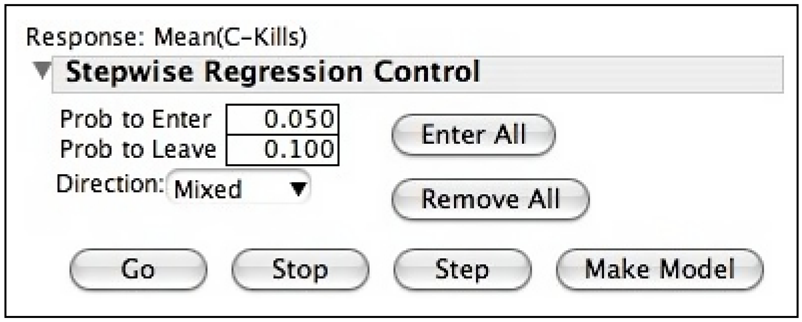
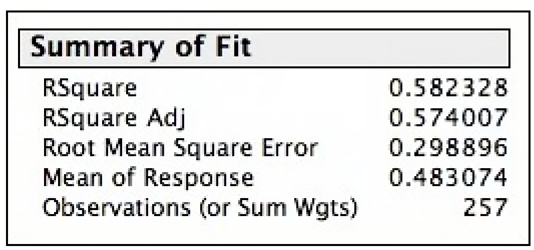


Figure 8. Stepwise Regression Control Panel in JMP.

The summary of fit shown in Figure 9 illustrates the R-squared (R^2) and adjusted R^2 values for the resulting model. These are statistical measures that indicate the proportion of variation in the response attributable to terms in the model, as opposed to random error. An R^2 value of 1.0 would indicate the model perfectly fit the data.



Summary of Fit	
RSquare	0.582328
RSquare Adj	0.574007
Root Mean Square Error	0.298896
Mean of Response	0.483074
Observations (or Sum Wgts)	257

Figure 9. Summary of Fit Resulting from Stepwise Regression for Main

The adjusted R^2 value is especially useful in stepwise procedures because it provides a better comparison of "fit" across models by using the degrees of freedom in its computation.[48] The adjusted R^2 value shown in Figure 9 of 0.57 will be considered a baseline against which to judge other regression models for this scenario.

After conducting the stepwise reduction procedure, the terms with a statistically significant impact on the regression model are shown in Figure 10. The results are consistent with the findings for the partition tree—namely target speed and JTAC sensor range contributing the most to the response. The column labeled "Scaled Estimate" provides the scaled regression coefficients that could be used to calculate a value for the expected proportion of target kills for a given set of input variables. The scaling provides a meaningful way to compare coefficients whose corresponding factors may have different units. A clarifying example is provided in Appendix C. Calculations performed in this vein are only valid for parameter values within the range of factor settings used to generate the original set of data. The fact that the coefficient for target speed has a negative value indicates that increases in speed reduce the calculated value of the response, which is in line with intuition and previous findings.

Scaled Estimates

Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.4830739	0.018645	25.91	<.0001
Tgt_C_Spd	-0.497853	0.032169	-15.48	<.0001
NEW_ImpRad	0.0654849	0.032162	2.04	0.0428
NEW_PdC	0.0697697	0.032091	2.17	0.0306
AC_Spd	0.0808914	0.032169	2.51	0.0125
JTAC_SnsrRng	0.3137775	0.032169	9.75	<.0001

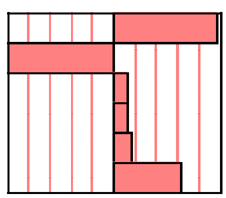


Figure 10. Scaled Estimates of the Regression Coefficients in the Main Effects Only Stepwise Reduced Statistical Model for Target Kills as the MOE.

48 Jay L. Devore, Probability and Statistics for Engineering and the Sciences, 6th Edition, 2004, Thomson Brooks/Cole Publishers, 2004, p. 580.

Running the stepwise reduction on all two-way interactions and 2nd order polynomial effects provides the next regression model. Figure 11 displays the scaled estimates of the coefficients. For this figure, the terms have been sorted based on the value of the scaled estimate. This selection of terms produced an adjusted R^2 value of 0.63, which indicates a modest improvement in the explanatory power of the statistical model, compared to the model with only main effects considered. This model does, however, provide insight into the interactions between the parameters.

Scaled Estimates

Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.4665227	0.039241	11.89	<.0001
JTAC_SnsrRng	0.3138202	0.029916	10.49	<.0001
(JTAC _TLEmu-55.0039)*(JTAC _TLEmu-55.0039)	0.1676852	0.05929	2.83	0.0051
(AC_LnchIntrvl-20.0016)*(AC_LnchIntrvl-20.0016)	0.1306483	0.060957	2.14	0.0331
(Tgt_C_Spd-12.0012)*(NEW_SnsrRng-2000.03)	0.1281817	0.055357	2.32	0.0214
(NEW_PdC-0.92502)*(C2_DecTime-105.001)	0.1059225	0.054574	1.94	0.0534
AC_Spd	0.0803891	0.029918	2.69	0.0077
NEW_PdC	0.0716894	0.02985	2.40	0.0171
NEW_ImpRad	0.0634571	0.02993	2.12	0.0350
NEW_SnsrRng	0.0574092	0.029921	1.92	0.0562
AC_LnchIntrvl	0.0424873	0.02993	1.42	0.1570
JTAC _TLEmu	0.0418568	0.029924	1.40	0.1632
C2_DecTime	-0.038308	0.029928	-1.28	0.2018
WCN_Rel	-0.054672	0.028912	-1.89	0.0598
(JTAC_SnsrRng-2750.01)*(JTAC_SnsrRng-2750.01)	-0.250201	0.061826	-4.05	<.0001
Tgt_C_Spd	-0.4973	0.029918	-16.62	<.0001

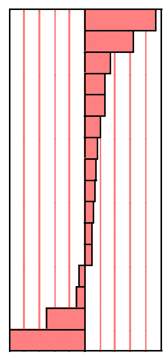


Figure 11. Scaled Estimates of the Regression Coefficients for the Stepwise Reduced Statistical Model with all Second Order Terms Considered.

It should also be noted at this point that several of the terms listed do not appear to be statistically significant at the .05 level—indicated by a "Prob > |t|" value greater than 0.05. Specifically, the significance values of WCN Reliability, C2 Decision Time, and JTAC TLEmu fall well outside of this range. This effect is a result of statistical precedence, which indicates terms considered significant in higher order interactions should also be included in the model as main effects, regardless of their individual significance.

Figure 12 shows the interaction profiles for three of the terms in the regression model. The vertical axis along the left side indicates the value of the response variable, in this case the proportion of target kills. The scale along the bottom indicates the range of settings for the term listed in the respective column. The numbers on the interior of the plot correspond with the low and high settings for the term listed in that particular row. For example, the plot in the first row and second column displays the interaction between target speed and NEW sensor range. The values of 4 and 20 are the low and high settings for speed, respectively. The lines being nonparallel indicate an interaction between the terms is present in the response. Specifically, when the target's speed is low, the response is minimally affected by increasing the NEW's sensor range. If, however, the target speed is high, increases in the NEW's sensor range have a significant impact on the proportion of target kills. This finding is consistent with the left branch of the partitioning tree shown previously in Figure 7. Also of interest is the large gap between the lines on the top row. This is indicative of the individual effect target speed has on the response.

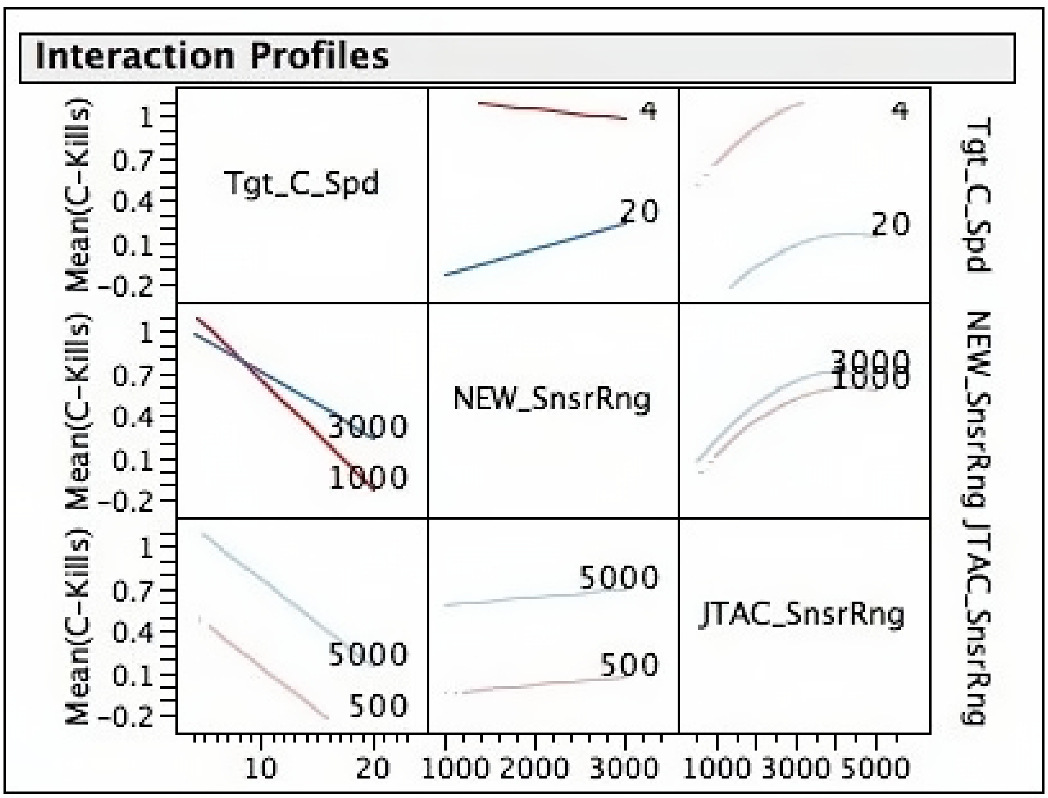


Figure 12. Plot of Selected Interaction Terms in a Regression Model for Target Kills

As shown by the distribution in Figure 13, a large number of DPs resulted in zero target kills. This is of particular interest considering the data used for the analysis is summary data—meaning all 100 replications of the DP would have to result in missing the target for it to register as a proportion equal to zero. As may be expected from previous results, the distributions for JTAC sensor range and target speed shown in Figure 14 further illuminate their effect on target kills. The figure is generated from only the 119 DPs with a mean response of zero and illustrates a significant portion of the data contains low sensor ranges and high speeds. It appears obvious these two terms are combining to create a threshold where the simulation model indicates the system's capability to identify, engage, and prosecute the target is unwieldy. A contour plot is often a useful tool to explore this possibility.

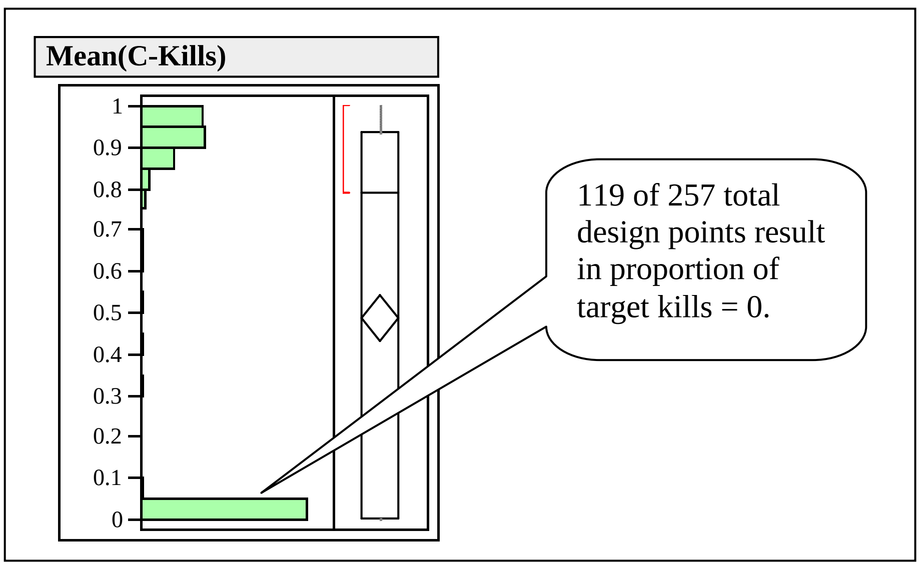


Figure 13. Distribution of Target Kills for all 257 Design Points in the Single Target Scenario.

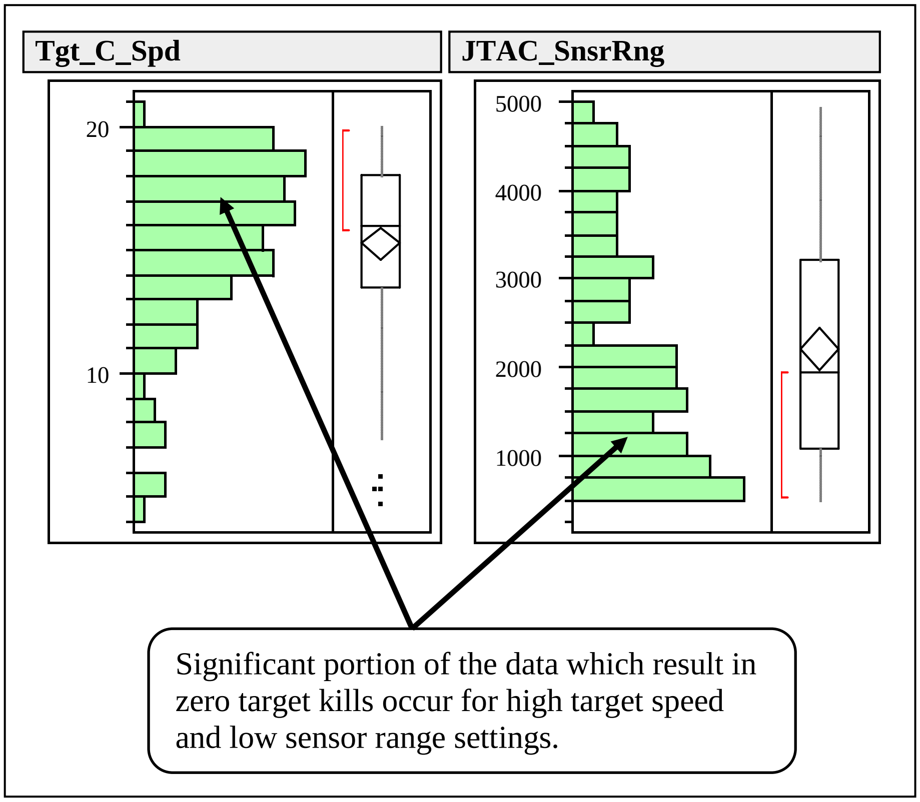


Figure 14. Distributions of Target Speed and JTAC Sensor Range for 119 Design Points Where No Target Kills Occur.

Figure 15 highlights the regions of the response where the combination of JTAC sensor range and target speed result in the gradations shown in the legend. The plot not only illustrates the combined effect of the two parameters, but also indicates a highly nonlinear aspect—as shown by the superimposed dotted line.

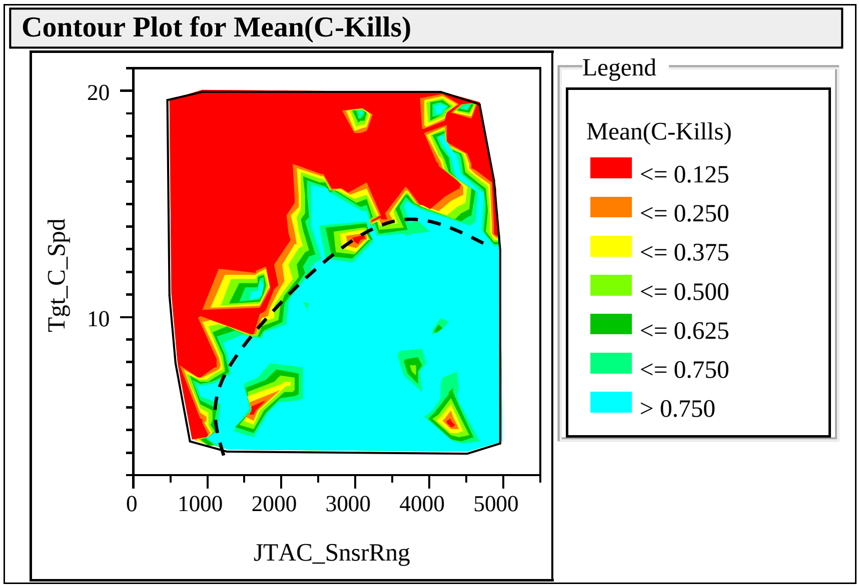


Figure 15. Contour Plot Highlighting the Proportion of Target Kills as a Function of the Combination Between JTAC Sensor Range and Target Speed.

In order to better understand the combined effect of JTAC sensor range and target speed, and to more fully explore other potentially influencing parameters, a new variable was created by dividing sensor range by speed. The resulting variable has units of time (specifically seconds) and helps reveal previously undiscovered aspects of the results. In a physical sense, the variable represents the time it would take a target moving in a straight line directly at the JTAC to pass completely through its sensor range. To avoid introducing correlation effects into the statistical models, analysis using this new variable was accomplished with the original variables for JTAC sensor range and target speed excluded.

The partitioning tree shown in Figure 16 includes the new variable and reveals insight into the effect of C2 decision time and launch aircraft speed. Within the context of factor ranges used in this scenario, the first two splits indicate threshold values for a notional time variable given by dividing the range and speed variables as discussed. The results indicate a time value exceeding 305 seconds produces favorable system performance—a proportion of target kills near 90%. If the time value falls between 197 and 305 seconds, then the simulation model suggests C2 decision time and aircraft speed play a critical role in overall system performance. Specifically, when the decision to initiate an attack sortie can be made in less than two minutes and the attack aircraft can fly to its launch standoff distance faster than 180 m/s (approximately 400 mph), then the estimate for proportion of kills increases from 55% to nearly 85%.

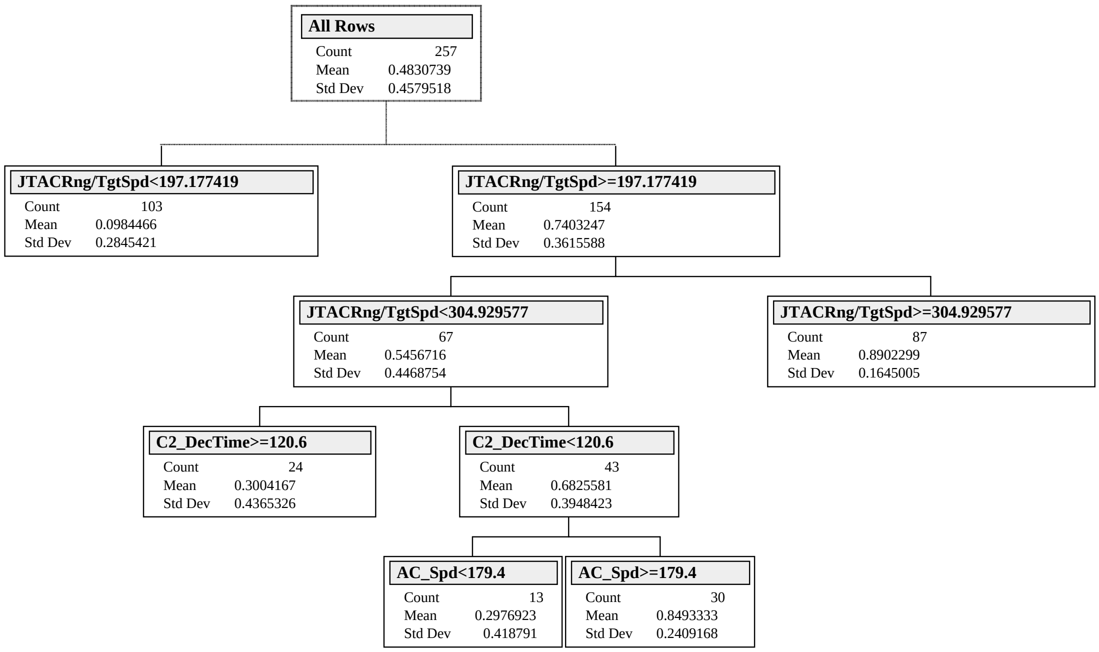


Figure 16. Partitioning Tree for Proportion of Target Kills with JTAC Sensor Range and Target Speed Combined Into One Variable.

C. RESULTS FOR THE TWO-TARGET SCENARIO

The second experiment involved the examination of NEW system effectiveness for the case of one mobile target, one dismounted high-value target (HVT), a ground-based weapon controller, and an aircraft equipped with two NEWs. The DoE included 27 factors, 257 design points (DP), and 100 replications of each DP.

Results for system effectiveness against the mobile vehicle are very similar to the one target case, with strong influence of the outcome based on JTAC sensor range and target speed. For the HVT, though, the factors most influential on the proportion of kills are characteristics of the weapon itself.

Figure 17 illustrates the potential effect of NEW impact radius on a target moving at speeds characteristic of a dismounted patrol. The HVT speed for this experiment ranged from 0.5 to 4 m/s—the difference between sauntering around and running just under seven minute miles. Overall, the simulation results show an 88% proportion of HVT kills. For NEW impact radii exceeding 5.4 meters and probability of kill (Pk) greater than 0.92, the kill level approaches 95%. As a reminder, for this research, Pk indicates the likelihood of successful detonation upon impact. It can also be thought of as a conditional probability, meaning the probability a target is destroyed given its location is within the blast radius. On the left branch of the tree, the results show the precision of the NEW sensor (i.e., TLE) improves system performance if the blast radius is less than 5.4 meters. The same explanation applies to the DPs for the larger impact radius, in cases where the Pk value is less than 0.92.

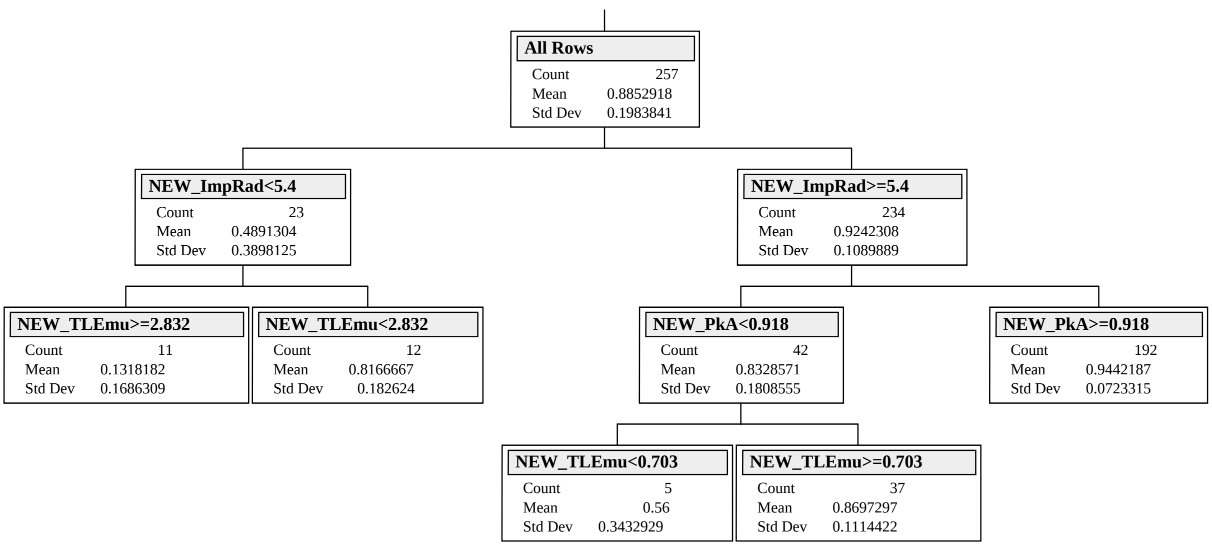


Figure 17. Partitioning Tree for Proportion of HVT Kills.

The output generated for this research did not support an indication into whether a specific kill resulted from a redirected NEW or one launched specifically designated for the HVT. The next section, however, reveals insight regarding the effects of having only one NEW available for the attack sortie.

D. ADDITIONAL FINDINGS

1. Results for Two Targets When Only One NEW is Available

The results in this section were obtained using the same DoE as in the previous two-target case. The difference here is the fact that only one NEW was available on the attack aircraft.

Figure 18 portrays the results for proportion of HVT kills. As previously noted, the intent of this analysis approach is to gain insight into which factors most significantly affect the response variable. Therefore, the reader is cautioned to not place undue influence on the value of the MOE itself, but instead to consider the relative changes in the response based on the specific value of the parameter under examination.

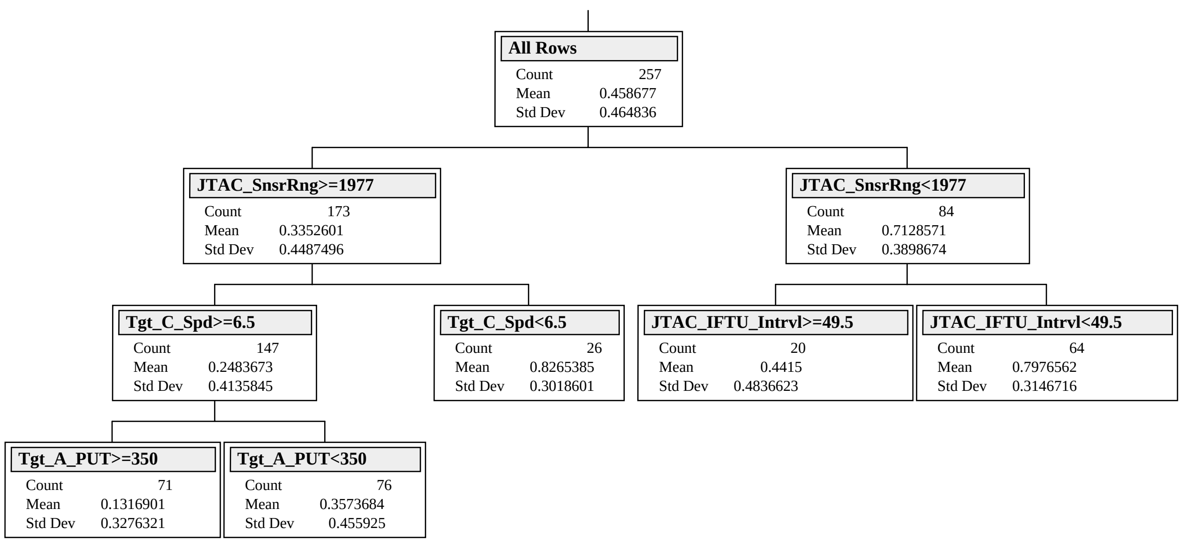


Figure 18. Partitioning Tree for Proportion of HVT Kills When Only One NEW is Available

Unlike results for the one target case, decreases in JTAC sensor range tend to improve the value of the response. This is likely the influence of early detection in the simulation of the mobile vehicle target. If the JTAC's sensors pick up the vehicle too soon, then the attack sortie is initiated and the resulting early launch of the NEW limits the ability of the weapon to respond to a request for redirect to the HVT. In fact, in some cases, the NEW is actually flying in autonomous seeker mode by the time the priority target appears, and therefore nonresponsive to communications through the WCN. This logic is further supported by the results in Figure 18 for larger JTAC sensor ranges (i.e., left initial branching). Improvements in the subsequent split indicate a drastic difference in the MOE if the vehicle target is moving slow—thereby increasing the time before initial detection. As a final point on this figure, observe that even when considering the DPs where JTAC sensor range and vehicle target speed are working against HVT success, the priority target may still appear in time to initiate a NEW redirect if it materializes in the scenario less than 350 seconds after the start.

V. CONCLUSIONS

A. ANALYSIS SUMMARY

This research considered Network Enable Weapon (NEW) scenarios involving a ground-based Joint Terminal Attack Controller (JTAC), a single launch aircraft, and two target types. The targets were either characteristic of a mobile tracked vehicle or a dismounted patrol. The dismounted patrol (when present in the scenario) represented a high-value target (HVT) and, therefore, was considered a higher priority. The simulation model contained six agent types and allowed for the exploration of effects and interactions for up to 27 parameters, which, of course, would be very difficult to accomplish in a live test.

For the scenario involving one mobile target, the results indicate a significant nonlinear interaction exists between the speed of the target and the sensor range of the JTAC. Specifically, for targets moving less than approximately 30 mph and a JTAC sensor range exceeding two kilometers, the model indicates an 80% improvement in the system's ability to identify, track, engage, and kill the target. Within the ranges of parameter settings used in the design, these findings hold regardless of the other factor settings. JTAC sensor range and target speed were combined to create a parameter that notionally represents the time a target is observable by the ground controller. This approach revealed insight into the effect of Command and Control (C2) decision time and the aircraft's speed. When the two factors combine to provide moderate target availability, system performance increases dramatically if the amount of time to respond to the Close Air Support (CAS) request is kept below two minutes and the strike aircraft proceeds to the weapon launch point at a speed greater than 400 mph.

In scenarios involving the vehicle target and the HVT, the results vary depending on the weapons load of the strike aircraft. For an aircraft carrying two NEWs, the ability to successfully engage the HVT is highly dependent on the weapons' impact radius and accuracy. When only one weapon is available, the ability to attack the HVT is significantly influenced by the timing of the scenario. For all designs used in this research, the vehicle target appears 10 seconds after the start of the simulation run. This means any attempts to prosecute a secondary target with only one weapon are likely to result from a redirected NEW. If the HVT appears too late in the scenario, or if the JTAC sensor range and vehicle target speed combine in a manner that results in an early CAS request, then the model indicates the system is unable to respond to a NEW redirect to the HVT.

B. KEY INSIGHTS SUPPORTING USE OF AGENT-BASED MODELING (ABM) IN TEST PLANNING

The overall objective of this research was to evaluate the use of ABM as a tool for enhancing joint test and evaluation. As a proof of concept, this thesis indicates ABM, combined with efficient experimental design, provides relatively quick insight into system-of-systems performance for a NEW construct. The simulation model can easily be tailored for specific scenarios. When paired with a variety of designs, a myriad of factor settings can quickly be explored in order to gain insight into specific areas of interest.

Conducting actual live tests for a NEW scenario will involve months, if not years, of planning, and cost several millions of dollars.[49] Using ABM techniques before conducting such events to understand potential interactions and system capabilities is well worth the investment. When properly combined with the right simulation tools, the concepts of efficient experimental design allow for an investigation of system performance across a broad spectrum of parameters and factor settings. Considering the broad uncertainties and complex interactions typical of military conflict, ABM offers a worthwhile analytical approach to explore elements of warfare that might otherwise be too costly or time intensive to study by other means.

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[49] Based on estimates provided by JTEM for an August 2007 planned test event.

C. RECOMMENDATIONS FOR FUTURE RESEARCH

This research is the first known attempt to investigate the application of ABM and efficient experimental design in support of JTEM test planning. The overall concept appears promising, but there are many aspects of the tools and techniques used in this thesis yet to be fully explored.

1. Experimental Design

The designs in this thesis were structured to quickly explore the key interactions in a NEW system-of-systems construct. Many of the initial experiments were used to error-check the model—making it critical to insure the simulations could be conducted in a short amount of computer processing time on one machine. Additionally, once the model was deemed sufficiently stable for conducting analysis, there was limited time to fully explore a broader range of parameters and parameter settings. Future efforts should consider increasing the number of replications for each design point beyond the 100 used in this thesis. Also, there are advances to consider in the application of nearly orthogonal, space-filling techniques, offering an increase in the number of factors and factor levels. Each of these approaches will likely result in longer computer run times for the experiment, but may reveal additional insights as well.

The results indicate a nominal increase in the predictive power of the regression formula when higher-order effects are added to the main effects. This suggests a sequential screening design may be useful in developing an initial estimate of which factors to consider in the design. The space-filling attributes of the Nearly Orthogonal Latin Hypercube (NOLH) design, however, are still required to gain insight into the complex interactions among the factors.

2. Simulation Model

The simulation model is essentially a prototype constructed to facilitate a proof of concept investigation of ABM applied to test planning. There are many enhancements capable of improving the breadth of applications to the NEW construct, a few of which are provided here.

- **Use of an Unmanned Aerial Vehicle (UAV) to identify and track targets and act as the third-party weapon controller:** The current research was limited to a ground-based controller. The extension to an aerial based controller opens the possibility of increased observation time on the target may be one approach to addressing the issue of high-speed targets.
- **Launch aircraft providing In-Flight Target Updates (IFTUs):** Currently, the model only supports in-flight targeting updates from the JTAC. In addition to adding IFTU capability to the launch aircraft, another extension would involve conditions in which the NEW is designated for direct attack mode—meaning the weapon goes directly into an autonomous mode and engages the target with its own sensors upon launch.
- **NEW redirect logic:** A simplified approach was used to determine whether or not the NEW could comply with a request to redirect to a different target. A more thorough physics-based representation is recommended to more accurately portray actual weapon performance capabilities.
- **Terrain effects:** This research considered operations on a flat surface. Adding terrain and/or building features to the model will increase analysis into the issues of line-of-sight limitations.
- **Target awareness:** In a real-world context, targets may become aware they are being tracked and potentially targeted and will likely alter their behaviors upon such recognition. Advancements to the model should support an analysis into this behavior.
- **JTAC FOV:** For both ground-based and UAV controllers, the sensors are typically constrained to a specific field of view (FOV). This research considered a 360-degree FOV, which is a somewhat unrealistic limitation.
- **Randomized factor settings:** "Scripted" settings for events such as target initial locations and waypoints were used for this research. Randomizing these and other factor settings may reveal additional insights and more accurately represent real-world dynamics. Other factors to consider for random effects include target pop-up time, number of targets, target speed, and target duration.

- **Fratricide and collateral damage:** Operations in urban or constrained environments are prevalent in today's warfare. Modeling the potential impact to unintended targets, whether friendly or neutral, may provide a useful measure of system effectiveness.
- **Target identification to kill output measure:** Including time from target identification to kill may be a useful additional measure.

3. Scenarios and Factors

There are obviously numerous scenarios possible for both real-world NEW engagements and joint test events. While a limited set were explored in this research, the simulation model is easily adaptable to a wide range of possibilities.

- **Time Sensitive Targeting:** Target disappears once route is complete.
- **Launch aircraft orbiting:** Rather than have the launch aircraft always initiate from a set point in space, using an orbit might reveal effects dictated by the size, type, or direction of the orbit pattern.
- **Kill criteria:** Different target sets may not require catastrophic destruction. In such cases, the concept of obtaining a mobility or firepower kill may be a sufficient objective and should be modeled accordingly.
- **Multiple targets:** As in real life, an engagement may contain multiple targets and targets of various types and priorities. An additional extension would be to add "legacy" weapons that aren't network enabled to the aircraft load and investigate the effects of decisions regarding which weapon type to use against a specific type of target or target behavior.
- **JTAC Pd toggle:** As indicated in Chapter III, the JTAC's set detection probability toggles to 1.0 (meaning certainty) once a target is initially detected. This was done to simulate a focused attention on a target, but may not always be realistic. Conducting model runs in which the Pd remains at the setting for a particular design point (DP) throughout the engagement may reveal different results.

4. Process

There are several aspects to the model design and implementation process that could be improved or expanded. Possibly the most beneficial expansion would be to include even more discussions with subject matter experts (SMEs) regarding the model's functionality and capabilities. The "face validity" gained by exposing the model to SME input and evaluation would increase the credibility of the results and move the entire process further from an academic endeavor and into an operationally beneficial product.

From a usability perspective, the process of initiating model runs and generating model output could be improved to enhance the portability of the product. As it currently stands, the model requires extensive user understanding of computer programming interfaces in order to design and implement a specific experiment. Additionally, the output generates a massive amount of data files that must be processed with tools secondary to the model itself—generating another layer of analytical complexity.

It is anticipated that students and faculty from NPS will continue working with JTEM to expand on this and other research efforts supporting joint test planning. The author was requested to comment on the general usefulness of the current model in addressing JTEM requirements. The responses are provided in Appendix D.

APPENDIX A. SUMMARY DESCRIPTION OF PARAMETERS IN THE SIMULATION MODEL

This table provides a summary description of the factors in the simulation model. It can be used as a means of reference when viewing figures in the analysis to better understand the link between factor name, what that factor represents, and the units of measure.

Factor Name	Description	Units
JTAC_Spd	JTAC (i.e., third-party weapon controller) Speed	meters/sec
JTAC_SnsrRng	JTAC Sensor Range	meters
JTAC_PdA	JTAC Prob Detection for HVT	n/a
JTAC_PdC	JTAC Prob Detect for Mobile Vehicle Target	n/a
JTAC_MTDF	JTAC Multi-Target Degradation Factor	n/a
JTAC_TLEmu	JTAC Mean Target Location Error	meters
JTAC_TLEsigma	JTAC Target Location Error Standard Deviation	meters
JTAC_IFTU_Intrvl	JTAC In-flight Target Update Interval	seconds
NEW_Spd	NEW Speed	meters/sec
NEW_ImpRad	NEW Impact Radius	meters
NEW_SnsrRng	NEW Sensor Range	meters
NEW_TLEmu	NEW Mean Target Location Error	meters
NEW_TLEsigma	NEW Target Location Error Standard Deviation	meters
NEW_PdA	NEW Prob Detection for HVT	n/a
NEW_PdC	NEW Prob Detection for Mobile Vehicle Target	n/a
NEW_PkA	NEW Prob Kill for HVT	n/a
NEW_PkC	NEW Prob Kill for Mobile Vehicle Target	n/a
Tgt_A_Spd	HVT Speed	meters/sec
Tgt_A_PUT	HVT Pop-up Time	seconds
Tgt_C_Spd	Target C Speed	meters/sec
Tgt_C_PUT	Target C Pop-up Time	seconds
AC_Spd	Aircraft Speed	meters/sec
AC_LnchDist	Aircraft Stand-off Launch Distance	meters
AC_UpdtReq	Aircraft Requirement for Recency of Target Info	seconds
AC_LnchAtmpts	Aircraft Number of Launch Attempts	n/a
AC_LnchIntrvl	Aircraft Interval Between Launch Attempts	seconds
WCN_Rel	Weapon Control Network Reliability	n/a
WCN_Lat	Weapon Control Network Latency	n/a
C2_DecTime	Command and Control Decision Time	seconds

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APPENDIX B. EXPERIMENTAL DESIGN FOR THE SINGLE TARGET SCENARIO

Low	4	140	3	1000	0	0	0.85	0.9	154	18500	10
High	20	200	30	3000	5	2	1	1	254	74000	45
Decimals	2	0	1	0	2	2	2	2	1	0	0
Design Pt #	Tgt_C_Spd	NEW_Spd	NEW_ImpRad	NEW_SnsrRng	NEW_TLEmu	NEW_TLEsigma	NEW_PdC	NEW_PkC	AC_Spd	AC_LnchDist	AC_UpdtReq
1	13.5	178	27.3	3000	4.38	0.38	0.89	0.91	172.4	37361	24
2	17.44	183	17.3	2945	4.22	1.09	0.94	1	242.7	46900	11
3	5.88	198	24.9	2883	4.45	1.29	0.88	0.91	168.5	70531	39
4	10.38	184	23.1	2758	4.75	0.3	0.99	1	249.3	54271	30
5	13.81	196	24.4	2508	3.44	0.13	0.86	0.93	161.8	46467	16
6	19.31	192	27.5	2469	4.77	1.45	0.98	0.98	224.7	69230	25
7	11.06	171	17	2531	2.93	1.34	0.85	0.93	186	26521	42
8	9.88	196	23	2398	3.4	0.97	0.92	0.98	219.2	42131	42
9	18.88	163	24.2	2477	4.9	0.35	0.99	0.95	197	28689	33
10	17.81	143	19.5	2133	2.75	1.91	0.91	0.98	248.9	25871	30
11	11.75	166	16.6	2953	2.99	1.8	0.95	0.92	194.2	54488	14
12	5.19	162	21	2539	3.11	0.98	0.92	1	217.7	58391	25
13	14.06	164	24.5	2289	3.32	0.74	0.96	0.9	201.3	63594	33
14	15.5	150	24.6	2977	2.56	1.43	0.9	0.97	220	51887	40
15	4.63	147	17.2	2523	2.81	1.48	0.93	0.9	168.8	24570	21
16	8.31	164	22.5	2875	4.28	0.21	0.85	0.98	211.8	28256	23
17	16.75	194	13	2281	3.3	0.31	0.93	0.91	186.8	36928	22
18	16.81	172	10.6	2703	3.38	1.55	0.99	0.96	216.9	44949	16
19	11.56	189	4.1	2742	3.95	1.35	0.89	0.92	163.8	56873	28
20	8.44	185	10.3	2555	4.59	0.93	0.97	0.99	234.9	61426	40
21	16.56	188	4.9	2969	4.82	0.75	0.85	0.91	170.8	69881	20
22	13.75	194	6.7	2734	4.12	1.53	0.96	0.99	252.4	45383	20
23	11.94	171	16.1	2563	3.63	1.38	0.88	0.92	189.5	34977	44
24	9.31	185	5	2633	3.28	0.95	0.92	0.97	228.2	32592	34
25	16.69	153	13.4	2070	4.98	0.14	0.94	0.93	159.5	41264	37
26	18.5	163	4.2	2367	4.43	1.52	0.88	0.95	250.1	35193	28
27	11.69	170	14.9	2211	4.04	1.44	0.95	0.93	199.7	49285	25
28	8.13	160	12.9	2391	2.71	0.95	0.93	0.96	234.5	72916	18
29	18.38	152	14	2672	3.87	0.98	0.96	0.92	191.9	65545	38
30	12.5	152	7.3	2500	2.87	1.8	0.87	0.98	227.8	54055	24
31	7	168	6.2	2344	4.55	1.42	0.95	0.94	159.9	25221	16
32	8.06	157	13.8	2078	4.67	0.42	0.91	0.96	243.8	30641	12
33	17.38	178	30	1203	3.54	0.66	0.87	0.96	196.6	26305	16
34	16	191	29.3	1938	2.89	1.81	0.94	0.92	229	39529	18
35	9.25	192	28.4	1375	2.85	1.16	0.88	0.98	163	49068	40
36	11.38	187	26.7	1508	4.84	0.86	0.98	0.92	213	48635	36
37	12.56	199	23.4	1414	4.16	0.84	0.86	0.99	199.3	44516	12
38	14.94	192	22.8	1188	2.91	1.15	1	0.92	238.4	49719	15
39	10.31	187	23.7	1961	3.46	1.51	0.87	0.98	186.4	29123	40
40	8.88	189	21.9	1516	3.57	0.94	0.96	0.95	227.4	24787	44
41	19.75	168	22.9	1430	3.55	0.33	0.95	0.96	189.2	24354	32
42	17.88	159	18.3	1781	3.09	1.95	0.92	0.92	222.8	27822	35
43	7.5	164	29.4	1992	4.73	1.82	0.95	0.97	195.8	62943	21
44	6.94	158	23.8	1664	3.13	0.52	0.91	0.95	251.7	62510	29
45	14.25	150	20.4	1406	2.54	0.39	0.96	0.98	157.5	58174	26
46	17.63	155	29.7	1398	4.51	1.6	0.86	0.93	202	68363	31
47	6.06	160	23.6	1945	2.95	1.72	0.92	0.97	200.9	21102	17
48	7.56	168	28.3	1555	2.73	0.41	0.89	0.95	217.3	20885	13
49	14.31	200	12.7	1742	2.62	0.02	0.86	0.97	164.5	33242	13
50	19.81	198	7	1563	4.61	1.2	1	0.93	203.2	18934	12
51	7.81	196	6.5	1078	4.3	1.77	0.88	0.97	193.8	53404	42
52	5	193	9	1539	3.24	0.32	1	0.9	243.1	53621	45
53	15.81	185	3.4	1141	2.77	0.81	0.89	0.99	184.9	73133	16
54	13.06	184	6.6	1273	3.26	1.47	0.96	0.9	207.5	56223	14
55	4.38	186	8.9	1969	4.96	1.59	0.88	0.99	174.7	25004	32
56	7.69	182	8	1148	4.24	0.07	0.96	0.94	254	37578	29
57	16.06	156	15.6	1773	3.79	0.5	0.94	0.99	169.2	26088	35
58	15.75	166	11.5	1086	4.1	1.45	0.9	0.94	225.5	22186	45
59	7.75	141	13.7	1883	4.14	1.41	0.97	0.96	162.2	73783	25
60	8.81	154	11.2	1734	4.47	0.38	0.86	0.94	233.7	74000	21
61	20	161	7.4	1813	3.52	0.05	1	0.98	166.9	59691	41
62	19.56	141	9.8	1320	4.02	1.98	0.9	0.94	213.4	66846	33
63	4.94	154	11.9	1234	3.18	1.84	0.99	0.96	161.4	33025	10
64	5.94	144	15.4	1797	4.57	0.16	0.88	0.91	215.3	41047	22
65	15.25	171	22.1	2750	0	0.3	0.87	0.92	253.2	20451	26
66	16.88	195	18.6	2688	0.14	1.27	0.94	0.99	155.2	23486	18
67	9.81	192	18.4	2781	0.29	1.71	0.91	0.91	247.8	53838	44
68	5.38	179	29.2	2898	0.61	0.72	0.98	0.99	168.1	56006	34
69	16.13	173	25.5	2375	1.23	0.37	0.9	0.91	227	65762	18
70	17.13	179	18.7	2906	1.33	1.52	0.93	0.97	179.4	56656	10
71	6.75	200	21.7	2172	1.17	1.83	0.87	0.94	230.6	21535	35
72	5.69	191	22.3	2359	1.5	0.34	0.99	0.96	183.7	32158	28
73	12.88	155	22.2	2961	1.31	0.69	0.97	0.95	210.3	33459	42
74	14.44	151	19.7	2102	2.17	1.04	0.89	1	178.2	30424	41
75	4.13	150	28.5	2195	0.12	1.73	0.99	0.94	234.1	64895	19
76	6.44	146	19.9	2242	1.15	0.04	0.88	0.96	156	54705	23
77	12.38	158	16.7	2328	1.78	0.11	0.97	0.95	251.3	60559	43
78	18.75	152	27.4	2023	0.06	1.08	0.89	0.97	185.6	72482	32
79	6.25	162	18.9	2125	1.19	1.39	0.98	0.91	250.9	35410	17
80	9.63	145	17.8	2711	0.31	0.26	0.9	0.95	177	48418	19
81	12.13	182	15.9	2320	1.8	0.09	0.92	0.93	240.7	42348	12

Low	1	10	500	10	2	0.7	15	0.95	0	10
High	5	30	5000	100	20	1	45	1	2	200
Decimals	0	1	0	0	0	2	1	2	2	1
Design Pt #	AC_LnchAtmpts	AC_LnchIntrvl	JTAC_SnsrRng	JTAC _TLEmu	JTAC_TLEsigma	JTAC_PdC	JTAC_IFTU_Intrvl	WCN_Rel	WCN_Lat	C2_DecTime
1	3	11.2	1273	32	7	0.76	16.5	0.96	0.48	15.2
2	1	12.7	2082	31	9	0.78	26.8	0.96	0.5	85
3	3	28.6	1590	24	3	0.7	27.9	0.96	0.88	45.6
4	4	30	570	29	10	0.82	27.1	0.96	0.38	55.3
5	2	12.3	4684	86	17	0.8	22	0.96	1.16	21.1
6	3	18.8	4508	92	20	0.71	27	0.96	0.7	36
7	5	23.2	4086	96	17	0.82	27.8	0.96	0.29	58.2
8	4	26.6	3559	96	19	0.78	18.5	0.97	0.15	33.8
9	3	15.9	3277	16	6	0.97	32.7	0.96	0.73	24.8
10	3	12.2	4209	35	10	0.93	29.5	0.96	0.58	20.4
11	4	20.4	4420	11	11	0.92	42.1	0.95	0.2	90.2
12	3	26	3260	38	7	0.92	34.7	0.96	0.01	94.6
13	2	11.6	2469	86	14	0.96	39.1	0.96	0.07	71.6
14	3	16.9	2486	97	13	0.98	43.6	0.95	0.69	31.5
15	4	29.1	1045	59	12	0.97	38.2	0.96	0.37	15.9
16	4	24.6	2627	69	18	1	44.3	0.97	0.81	93.1
17	4	13	1924	21	9	0.87	18.3	0.99	1.94	106.5
18	5	13.7	2680	37	8	0.79	15.6	0.98	1.23	123.6
19	3	25.3	553	19	5	0.76	29.2	1	1.13	32.3
20	2	24.2	1344	19	2	0.74	22.7	0.98	1.34	96.1
21	5	11.8	4033	72	19	0.81	28.5	0.98	1.45	121.3
22	3	14.8	3770	99	15	0.81	22.4	0.99	1.66	41.9
23	1	27.6	2557	83	15	0.78	15	0.98	1.1	95.4
24	1	29.5	4121	71	14	0.84	16.2	0.99	2	62.7
25	4	16.4	4104	49	4	0.99	35.5	0.99	1.13	50.1
26	3	17.9	2451	52	3	0.93	35	0.99	1.2	97.6
27	2	25.1	3682	36	10	0.96	40.8	0.99	1.84	70.1
28	2	21.3	4068	23	5	0.98	44.5	1	1.11	16.7
29	3	20.5	1678	74	14	0.93	39.4	0.99	1.83	18.9
30	5	16.6	2592	67	15	0.94	42.9	0.99	1.95	110.2
31	2	25	2100	71	19	0.95	34.1	1	1.63	89.4
32	3	28.3	1115	61	19	0.89	37	1	1.77	60.5
33	2	24	1186	74	6	0.96	27.5	0.97	0.27	184.4
34	1	29.1	711	54	10	0.85	23.7	0.99	0.79	186.6
35	5	17.1	1607	85	9	0.95	16.9	0.99	0.4	119.1
36	5	15.5	693	73	8	0.96	29.1	0.98	0.59	157.7
37	2	24.4	3752	22	18	0.91	25.4	0.97	0.09	101.3
38	2	24.3	3928	23	15	0.84	18.9	0.97	0.26	139.1
39	4	10.6	4824	46	11	0.87	24.8	1	0.42	182.9
40	4	16.3	3523	14	16	0.94	25.7	0.98	0.35	183.7
41	2	24.1	2732	78	11	0.83	36.1	1	0.34	129.5
42	1	20.9	2979	60	10	0.84	31.2	0.98	0.02	166.6
43	4	19.3	3963	77	3	0.72	30.1	0.99	0.68	169.6
44	4	17	4578	70	10	0.75	39.8	1	0.71	191.8
45	1	23.9	1871	43	12	0.78	41.8	0.99	0.49	174.8
46	2	22.6	2170	51	19	0.76	31.9	0.99	0.28	162.1
47	5	13.8	2416	44	12	0.82	29.8	0.98	0.09	148.8
48	3	15.3	2926	16	14	0.75	40.3	0.98	1.08	125.8
49	5	21.8	1836	84	4	0.92	21	0.96	1.28	182.2
50	4	29.8	1168	65	5	0.98	28.4	0.97	1.25	146.6
51	2	14.1	1098	89	7	0.94	24.3	0.96	1.98	117.6
52	2	18.3	2188	100	11	0.87	23.6	0.97	0.98	130.2
53	4	27.5	3699	30	14	0.88	19.1	0.96	0.96	153.2
54	4	20.3	4877	17	18	0.86	21.6	0.97	1.92	155.5
55	1	11.5	4754	30	17	0.98	18	0.97	1.16	118.4
56	1	12.7	4912	53	10	0.9	26.1	0.96	1.46	187.4
57	5	22.5	4895	63	4	0.77	43.9	0.97	1.38	124.3
58	3	20.6	3734	95	9	0.84	41.3	0.98	1.27	135.4
59	3	11.3	4965	85	5	0.73	37.5	0.96	1.09	171.1
60	3	17.7	3348	62	5	0.71	31.4	0.97	1.55	132.5
61	3	22.7	957	50	20	0.81	34.2	0.96	1.9	197
62	4	28.9	500	57	18	0.7	42.2	0.95	1.14	200
63	2	13.4	2398	12	16	0.74	42.4	0.97	0.98	158.4
64	2	19.2	2311	44	14	0.83	33.4	0.96	1.41	165.1
65	1	10.1	1010	43	14	0.75	41	0.95	1.48	122.8
66	2	10.2	834	45	16	0.85	35.3	0.96	1.87	196.3
67	4	25.5	2258	20	16	0.82	43	0.97	1.54	172.5
68	3	28	3207	31	16	0.81	31.3	0.97	1.48	102.8
69	2	15.2	3154	95	4	0.81	34.9	0.98	1.45	122.1
70	1	19	4350	87	3	0.81	44.9	0.96	1.55	110.9
71	3	27.9	4648	85	2	0.8	27.7	0.95	1.36	195.5
72	4	25.5	3453	82	3	0.71	41.4	0.95	1.2	100.5
73	3	18.4	4842	27	20	0.92	21.9	0.97	1.53	171.8
74	1	17.3	3383	47	15	0.9	19.9	0.97	1.57	105.7
75	4	23.8	4525	54	20	0.96	20.5	0.96	1.44	159.2
76	4	29	4473	27	13	0.93	22.9	0.96	1.59	179.2
77	3	13.8	869	76	7	0.99	16.3	0.96	1.52	140.6
78	2	18.5	1203	62	2	0.97	15.8	0.96	1.81	197.8
79	4	22.8	1238	64	11	0.91	15.2	0.96	1.64	150.3
80	3	23.4	2328	94	6	0.98	20.7	0.97	1.39	108
81	4	12	1660	38	18	0.73	33.8	1	0.3	142.1

Low	4	140	3	1000	0	0	0.85	0.9	154	18500	10
High	20	200	30	3000	5	2	1	1	254	74000	45
Decimals	2	0	1	0	2	2	2	2	1	0	0
Design Pt #	Tgt_C_Spd	NEW_Spd	NEW_ImpRad	NEW_SnsrRng	NEW_TLEmu	NEW_TLEsigma	NEW_PdC	NEW_PkC	AC_Spd	AC_LnchDist	AC_UpdtReq
82	18.44	175	5.1	2352	0.74	0.87	0.97	0.96	184.1	19801	26
83	10.56	174	6.8	2578	0.64	0.9	0.87	0.9	232.5	55355	33
84	11.25	198	12.5	2836	1.11	0.64	0.94	0.98	170.4	51670	38
85	15.38	190	15	2930	0.08	0.59	0.92	0.92	241.5	44299	24
86	13.88	175	12.4	2648	0.66	1.4	0.97	1	154.4	49502	18
87	4.88	181	3.2	2453	1.09	1.01	0.9	0.93	238	27172	29
88	10	183	7.1	2313	0.92	0.03	0.96	0.97	175.1	41480	38
89	17.31	157	9.5	2992	2.32	0.7	0.94	0.91	218.1	21752	35
90	13.31	163	7.9	2773	1.58	1.54	0.9	1	198.5	44732	43
91	8.94	143	7.6	2617	1.97	1.3	0.94	0.94	220.8	57957	22
92	8.56	163	5.8	2086	1.52	0.34	0.87	0.98	193.1	60125	19
93	15.31	170	11	2547	0.82	0.8	0.99	0.94	225.9	58607	28
94	13.25	146	8.3	2148	1.25	1.33	0.93	0.97	165.7	62727	28
95	10.88	165	12.8	2820	1.64	1.9	0.93	0.91	207.9	45166	16
96	4.5	167	5.3	2867	2.3	0.76	0.91	0.99	188.4	31725	24
97	16.38	180	26.6	1586	0.51	0.89	0.91	0.96	209.1	33676	13
98	13.19	181	25.8	1844	2.34	1.64	0.95	0.93	167.7	28473	25
99	5.44	187	27	1859	0.94	1.88	0.87	1	236	61209	32
100	5.06	195	28.6	1063	1.27	0.23	0.97	0.95	181.7	71182	36
101	19.94	198	21.6	1336	1.04	0.27	0.87	0.96	244.6	60992	19
102	18.19	189	28.7	1836	0.47	1.99	1	0.92	177.8	62293	23
103	7.06	184	18.8	1617	2.4	1.09	0.89	0.97	232.1	40180	36
104	11.31	179	21.4	1570	1.29	0.44	0.95	0.93	203.6	28039	43
105	19.44	140	29.5	1578	1.07	0.45	0.99	0.97	209.9	19150	29
106	17.19	147	17.9	1766	1.95	1.94	0.85	0.93	171.6	39963	43
107	8.38	151	19.1	1109	2.48	1.37	0.94	0.96	220.4	52104	11
108	9.5	167	19.8	1750	1.66	0.51	0.89	0.91	205.2	55789	15
109	14.56	154	20.9	1984	1.02	0.77	0.93	0.99	231.3	52754	41
110	14.81	166	16.8	1195	1	1.38	0.88	0.95	172.8	63160	40
111	7.38	145	18.2	1820	2.36	1.92	0.98	0.95	225.1	23053	24
112	5.31	144	26.1	1906	1.39	0.54	0.86	0.94	202.4	22836	18
113	14.63	193	12.2	1953	1.86	0.88	0.88	0.99	226.7	41914	11
114	12.19	191	11.8	1156	1.41	1.23	0.99	0.95	192.3	36061	14
115	11	193	8.7	1281	0.2	1.57	0.87	0.96	229.4	49936	37
116	6.31	197	5.2	1703	1.35	0.68	0.99	0.91	158.3	68580	44
117	19.69	181	3.9	1891	0.35	0.73	0.86	0.96	236.8	71832	17
118	12.81	197	7.7	1695	0.68	1.85	0.96	0.94	160.6	41697	24
119	10.44	175	10.4	1016	2.42	1.17	0.9	0.98	247	46684	40
120	10.06	181	12.3	1305	0.37	0.79	0.94	0.9	201.7	30857	34
121	15	141	3.1	1484	1.93	0	0.94	0.97	241.9	27389	28
122	19.25	167	6.1	1359	0.21	1.12	0.87	0.92	184.5	20234	34
123	10.63	164	8.2	1344	2.21	1.18	0.95	0.99	214.5	68797	21
124	9.13	163	15.3	1211	1.84	0.78	0.92	0.91	197.4	67063	14
125	18	160	9.1	1594	2.03	0.24	0.93	0.98	231.7	57740	38
126	17.5	169	14.5	1391	0.8	1.78	0.9	0.93	191.5	48852	28
127	5.75	166	5.4	1727	0.59	1.75	0.98	0.99	212.6	22402	24
128	4.81	149	4.8	1172	1.99	0.13	0.92	0.93	162.6	39313	20
129	12	170	16.5	2000	2.5	1	0.93	0.95	204	46250	28
130	10.5	162	5.7	1000	0.63	1.63	0.96	0.99	235.6	55139	31
131	6.56	157	15.7	1055	0.78	0.91	0.91	0.9	165.3	45600	44
132	18.13	142	8.1	1117	0.55	0.71	0.97	0.99	239.5	21969	16
133	13.63	156	9.9	1242	0.25	1.7	0.86	0.9	158.7	38229	25
134	10.19	144	8.6	1492	1.56	1.87	0.99	0.97	246.2	46033	39
135	4.69	148	5.5	1531	0.23	0.55	0.87	0.92	183.3	23270	30
136	12.94	169	16	1469	2.07	0.66	1	0.97	222	65979	13
137	14.13	144	10	1602	1.6	1.03	0.93	0.92	188.8	50369	13
138	5.13	177	8.8	1523	0.1	1.65	0.86	0.95	211	63811	22
139	6.19	197	13.5	1867	2.25	0.09	0.94	0.92	159.1	66629	25
140	12.25	174	16.4	1047	2.01	0.2	0.9	0.98	213.8	38012	41
141	18.81	178	12	1461	1.89	1.02	0.93	0.9	190.3	34109	30
142	9.94	176	8.5	1711	1.68	1.26	0.89	1	206.7	28906	22
143	8.5	190	8.4	1023	2.44	0.57	0.95	0.93	188	40613	15
144	19.38	193	15.8	1477	2.19	0.52	0.92	1	239.2	67930	34
145	15.69	176	10.5	1125	0.72	1.79	1	0.92	196.2	64244	32
146	7.25	146	20	1719	1.7	1.69	0.92	0.99	221.2	55572	33
147	7.19	168	22.4	1297	1.62	0.45	0.86	0.94	191.1	47551	39
148	12.44	151	28.9	1258	1.05	0.65	0.96	0.98	244.2	35627	27
149	15.56	155	22.7	1445	0.41	1.07	0.88	0.91	173.1	31074	15
150	7.44	152	28.1	1031	0.18	1.25	1	0.99	237.2	22619	35
151	10.25	146	26.3	1266	0.88	0.47	0.89	0.91	155.6	47117	35
152	12.06	169	16.9	1438	1.37	0.63	0.97	0.98	218.5	57523	11
153	14.69	155	28	1367	1.72	1.05	0.93	0.93	179.8	59908	21
154	7.31	187	19.6	1930	0.02	1.86	0.91	0.97	248.5	51236	18
155	5.5	177	28.8	1633	0.57	0.48	0.97	0.95	157.9	57307	27
156	12.31	170	18.1	1789	0.96	0.56	0.9	0.97	208.3	43215	30
157	15.88	180	20.1	1609	2.29	1.05	0.92	0.94	173.5	19584	37
158	5.63	188	19	1328	1.13	1.02	0.89	0.98	216.1	26955	17
159	11.5	188	25.7	1500	2.13	0.2	0.98	0.92	180.2	38445	31
160	17	172	26.8	1656	0.45	0.58	0.9	0.96	248.1	67279	39
161	15.94	183	19.2	1922	0.33	1.58	0.94	0.94	164.2	61859	43
162	6.63	162	3	2797	1.46	1.34	0.98	0.94	211.4	66195	39
163	8	149	3.7	2063	2.11	0.19	0.91	0.98	179	52971	37
164	14.75	148	4.6	2625	2.15	0.84	0.97	0.92	245	43432	15
165	12.63	153	6.3	2492	0.16	1.14	0.87	0.98	195	43865	19
166	11.44	141	9.6	2586	0.84	1.16	0.99	0.91	208.7	47984	43
167	9.06	148	10.2	2813	2.09	0.85	0.85	0.98	169.6	42781	40
168	13.69	153	9.3	2039	1.54	0.49	0.98	0.92	221.6	63377	15
169	15.13	151	11.1	2484	1.43	1.06	0.89	0.95	180.6	67713	11

Low	1	10	500	10	2	0.7	15	0.95	0	10
High	5	30	5000	100	20	1	45	1	2	200
Decimals	0	1	0	0	0	2	1	2	2	1
Design Pt #	AC_LnchAtmpts	AC_LnchIntrvl	JTAC_SnsrRng	JTAC _TLEmu	JTAC_TLEsigma	JTAC_PdC	JTAC_IFTU_Intrvl	WCN_Rel	WCN_Lat	C2_DecTime
82	4	11.9	1959	42	18	0.72	35.6	0.98	0.7	126.5
83	2	20.9	2363	31	17	0.82	38.8	0.98	0.03	157
84	2	20.2	1889	17	19	0.77	38.6	0.99	0.82	167.3
85	4	15.2	4719	95	7	0.83	32	0.99	0.6	154
86	4	14.1	3225	81	5	0.75	35.4	0.98	0.27	128.8
87	2	26.1	2697	70	4	0.71	36.9	0.98	0.95	131
88	3	26.7	4367	78	8	0.73	33.5	1	0.62	143.6
89	5	20.2	2838	19	14	0.9	20	0.98	0.53	142.9
90	4	11.3	3295	21	13	0.9	19.5	0.98	0.51	116.1
91	2	29.2	3945	51	16	0.92	22.1	1	0.22	152.5
92	2	26.9	2855	34	15	0.99	17.5	0.99	0.21	145.8
93	4	12.6	2029	62	10	0.97	21.7	1	0.18	161.4
94	3	10.4	1063	90	8	0.95	21.3	1	0.23	181.4
95	1	22.2	1713	92	9	0.86	15.9	0.99	0.04	111.7
96	2	24.9	1994	99	9	0.9	29.3	1	0.13	175.5
97	2	27.7	1695	77	15	0.87	36	1	1.24	82
98	1	21.3	1854	68	13	0.88	26	0.99	1.8	75.3
99	5	16.3	1256	58	16	0.94	36.7	0.99	1.76	76.1
100	4	16.5	1221	70	18	0.85	39.6	0.99	1.03	19.6
101	2	22.3	4191	13	5	0.89	34.8	1	1.15	62
102	3	25.2	3875	44	8	0.97	29.4	0.99	1.05	76.8
103	5	18.1	3365	46	9	0.85	31.1	0.99	1.84	73.1
104	4	14.4	4051	34	5	0.93	42.8	0.99	1.22	73.8
105	3	24.5	4701	63	17	0.82	19.3	1	1.7	24.1
106	3	28.4	4561	56	12	0.79	26.7	1	0.83	64.9
107	4	18.9	2785	93	16	0.81	19.6	0.98	1.69	30
108	5	14.6	4736	50	16	0.76	19.8	0.98	1.86	21.9
109	1	22	2012	49	7	0.7	18.4	0.98	1.33	47.1
110	3	20.5	1361	12	11	0.84	24.1	0.99	1.95	44.1
111	3	13.5	887	55	9	0.79	27.2	0.99	1.37	41.2
112	4	19.9	904	29	4	0.79	20.3	0.98	1.23	65.7
113	5	21.6	1484	84	19	0.98	36.6	0.97	0.74	39.7
114	4	27	2539	100	13	0.87	43.2	0.98	0.91	72.3
115	3	10.3	518	69	17	0.91	42.7	0.95	0.66	17.4
116	2	16.7	2609	68	20	0.9	34.5	0.98	0.32	68.6
117	3	25.8	3857	41	7	0.96	37.7	0.97	0.65	78.3
118	4	27.1	4859	28	3	0.96	32.6	0.95	0.93	29.3
119	2	17	3436	18	6	0.93	42.3	0.97	0.57	96.8
120	1	17.6	4771	57	9	0.94	33.6	0.97	0.39	59
121	4	29.5	3717	98	14	0.75	23.8	0.97	0.41	46.4
122	4	22	3119	75	18	0.71	28.2	0.97	1.01	82.7
123	2	13.6	2434	88	16	0.79	22.6	0.97	0.25	49.3
124	1	12.8	3998	75	11	0.84	15.4	0.97	0.33	36.7
125	5	29.3	1520	22	10	0.79	21.1	0.95	0.12	33
126	5	21.4	2504	28	10	0.72	16.6	0.97	0.44	53.8
127	3	14.3	1906	30	3	0.7	23.2	0.97	0.94	11.5
128	2	13.2	1326	37	7	0.87	29.6	0.97	0.11	10.7
129	3	20	2750	55	11	0.85	30	0.98	1	105
130	3	28.8	4227	78	15	0.94	43.5	0.99	1.52	194.8
131	5	27.3	3418	79	13	0.93	33.2	0.99	1.5	125
132	3	11.4	3910	86	19	1	32.1	0.99	1.12	164.4
133	2	10	4930	81	12	0.88	32.9	0.99	1.62	154.7
134	4	27.7	816	24	5	0.9	38	0.99	0.84	188.9
135	3	21.2	992	18	2	0.99	33	0.99	1.3	174
136	1	16.8	1414	14	5	0.88	32.2	0.99	1.71	151.8
137	2	13.4	1941	14	3	0.92	41.5	0.98	1.85	176.3
138	3	24.1	2223	94	16	0.73	27.3	0.99	1.27	185.2
139	3	27.8	1291	75	12	0.77	30.5	0.99	1.42	189.6
140	2	19.6	1080	99	11	0.78	17.9	1	1.8	119.8
141	3	14	2240	72	15	0.78	25.3	0.99	1.99	115.4
142	4	28.4	3031	24	8	0.74	20.9	0.99	1.93	138.4
143	3	23.1	3014	13	9	0.72	16.4	1	1.31	178.5
144	2	10.9	4455	51	10	0.73	21.8	0.99	1.63	194.1
145	2	15.4	2873	41	4	0.7	15.7	0.98	1.19	116.9
146	2	27	3576	89	13	0.83	41.7	0.96	0.06	103.5
147	1	26.3	2820	73	14	0.91	44.4	0.97	0.77	86.4
148	3	14.7	4947	91	17	0.94	30.8	0.95	0.88	177.7
149	4	15.8	4156	91	20	0.96	37.3	0.97	0.66	113.9
150	1	28.2	1467	38	3	0.89	31.5	0.97	0.55	88.7
151	3	25.2	1730	11	7	0.89	37.6	0.96	0.34	168.1
152	5	12.4	2943	27	7	0.92	45	0.97	0.9	114.6
153	5	10.5	1379	39	8	0.86	43.8	0.96	0	147.3
154	2	23.6	1396	61	18	0.71	24.5	0.96	0.87	159.9
155	3	22.1	3049	58	19	0.77	25	0.96	0.8	112.4
156	4	14.9	1818	74	12	0.74	19.2	0.96	0.16	139.9
157	4	18.8	1432	87	17	0.72	15.5	0.95	0.89	193.3
158	3	19.5	3822	36	8	0.77	20.6	0.96	0.17	191.1
159	1	23.4	2908	43	7	0.76	17.1	0.96	0.05	99.8
160	4	15	3400	39	3	0.75	25.9	0.95	0.38	120.6
161	3	11.7	4385	49	3	0.81	23	0.95	0.23	149.5
162	4	16	4314	36	16	0.74	32.5	0.98	1.73	25.6
163	5	10.9	4789	56	12	0.85	36.3	0.96	1.21	23.4
164	1	22.9	3893	25	13	0.75	43.1	0.96	1.6	90.9
165	1	24.5	4807	37	14	0.74	30.9	0.97	1.41	52.3
166	4	15.6	1748	88	4	0.79	34.6	0.98	1.91	108.7
167	4	15.7	1572	87	7	0.86	41.1	0.98	1.74	70.9
168	2	29.4	676	64	11	0.83	35.2	0.95	1.58	27.1
169	2	23.8	1977	96	6	0.76	34.3	0.97	1.65	26.3

Low	4	140	3	1000	0	0	0.85	0.9	154	18500	10
High	20	200	30	3000	5	2	1	1	254	74000	45
Decimals	2	0	1	0	2	2	2	2	1	0	0
Design Pt #	Tgt_C_Spd	NEW_Spd	NEW_ImpRad	NEW_SnsrRng	NEW_TLEmu	NEW_TLEsigma	NEW_PdC	NEW_PkC	AC_Spd	AC_LnchDist	AC_UpdtReq
170	4.25	172	10.1	2570	1.45	1.67	0.9	0.94	218.8	68146	23
171	6.13	181	14.7	2219	1.91	0.05	0.93	0.98	185.3	64678	20
172	16.5	176	3.6	2008	0.27	0.18	0.9	0.93	212.2	29557	34
173	17.06	182	9.2	2336	1.88	1.48	0.94	0.95	156.3	29990	26
174	9.75	190	12.6	2594	2.46	1.61	0.89	0.92	250.5	34326	29
175	6.38	185	3.3	2602	0.49	0.4	0.99	0.98	206	24137	24
176	17.94	180	9.4	2055	2.05	0.28	0.93	0.93	207.1	71398	38
177	16.44	172	4.7	2445	2.27	1.59	0.96	0.95	190.7	71615	42
178	9.69	140	20.3	2258	2.38	1.98	0.99	0.93	243.5	59258	42
179	4.19	142	26	2438	0.39	0.8	0.85	0.97	204.8	73566	43
180	16.19	144	26.5	2922	0.7	0.23	0.97	0.93	214.2	39096	13
181	19	147	24	2461	1.76	1.68	0.85	1	164.9	38879	10
182	8.19	155	29.6	2859	2.23	1.19	0.96	0.91	223.1	19367	39
183	10.94	156	26.4	2727	1.74	0.53	0.89	1	200.5	36277	41
184	19.63	154	24.1	2031	0.04	0.41	0.97	0.91	233.3	67496	23
185	16.31	158	25	2852	0.76	1.93	0.89	0.96	154	54922	26
186	7.94	184	17.4	2227	1.21	1.5	0.91	0.91	238.8	66412	20
187	8.25	174	21.5	2914	0.9	0.55	0.95	0.96	182.5	70314	10
188	16.25	199	19.3	2117	0.86	0.59	0.88	0.94	245.8	18717	30
189	15.19	186	21.8	2266	0.53	1.62	0.99	0.96	174.3	18500	34
190	4	179	25.6	2188	1.48	1.95	0.85	0.92	241.1	32809	14
191	4.44	199	23.3	2680	0.98	0.02	0.95	0.96	194.6	25654	22
192	19.06	186	21.1	2766	1.82	0.16	0.86	0.94	246.6	59475	45
193	18.06	196	17.6	2203	0.43	1.84	0.97	0.99	192.7	51453	33
194	8.75	169	10.9	1250	5	1.7	0.98	0.98	154.8	72049	29
195	7.13	145	14.4	1313	4.86	0.73	0.91	0.91	252.8	69014	37
196	14.19	148	14.6	1219	4.71	0.29	0.94	0.99	160.3	38662	11
197	18.63	161	3.8	1102	4.39	1.28	0.87	0.91	239.9	36494	21
198	7.88	167	7.5	1625	3.77	1.63	0.95	0.99	181	26738	37
199	6.88	161	14.3	1094	3.67	0.48	0.92	0.93	228.6	35844	45
200	17.25	140	11.3	1828	3.83	0.17	0.98	0.96	177.4	70965	20
201	18.31	149	10.7	1641	3.5	1.66	0.86	0.94	224.3	60342	27
202	11.13	185	10.8	1039	3.69	1.31	0.88	0.95	197.8	59041	13
203	9.56	189	13.3	1898	2.83	0.96	0.96	0.9	229.8	62076	14
204	19.88	190	4.5	1805	4.88	0.27	0.86	0.96	173.9	27605	36
205	17.56	194	13.1	1758	3.85	1.96	0.97	0.94	252	37795	32
206	11.63	182	16.3	1672	3.22	1.89	0.88	0.95	156.7	31941	12
207	5.25	188	5.6	1977	4.94	0.92	0.96	0.93	222.4	20018	23
208	17.75	178	14.1	1875	3.81	0.61	0.87	0.99	157.1	57090	38
209	14.38	195	15.2	1289	4.69	1.74	0.95	0.95	231	44082	36
210	11.88	158	17.1	1680	3.2	1.91	0.93	0.97	167.3	50152	43
211	5.56	165	27.9	1648	4.26	1.13	0.88	0.94	223.9	72699	29
212	13.44	166	26.2	1422	4.36	1.1	0.98	1	175.5	37145	22
213	12.75	142	20.5	1164	3.89	1.36	0.91	0.92	237.6	40830	17
214	8.63	150	18	1070	4.92	1.41	0.93	0.98	166.5	48201	31
215	10.13	165	20.6	1352	4.34	0.6	0.88	0.9	253.6	42998	37
216	19.13	159	29.8	1547	3.91	0.99	0.95	0.97	170	65328	26
217	14	157	25.9	1688	4.08	1.97	0.89	0.93	232.9	51020	17
218	6.69	183	23.5	1008	2.68	1.3	0.91	0.99	189.9	70748	20
219	10.69	177	25.1	1227	3.42	0.46	0.95	0.9	209.5	47768	12
220	15.06	197	25.4	1383	3.03	0.7	0.91	0.96	187.2	34543	33
221	15.44	178	27.2	1914	3.48	1.66	0.98	0.92	214.9	32375	36
222	8.69	170	22	1453	4.18	1.2	0.86	0.96	182.1	33893	27
223	10.75	194	24.7	1852	3.75	0.67	0.92	0.93	242.3	29773	27
224	13.13	175	20.2	1180	3.36	0.1	0.92	0.99	200.1	47334	39
225	19.5	173	27.7	1133	2.7	1.24	0.94	0.91	219.6	60775	31
226	7.63	160	6.4	2414	4.49	1.11	0.94	0.94	198.9	58824	42
227	10.81	159	7.2	2156	2.66	0.36	0.9	0.97	240.3	64027	30
228	18.56	153	6	2141	4.06	0.12	0.98	0.9	172	31291	23
229	18.94	145	4.4	2938	3.73	1.77	0.88	0.95	226.3	21318	19
230	4.06	142	11.4	2664	3.96	1.73	0.98	0.94	163.4	31508	36
231	5.81	151	4.3	2164	4.53	0.01	0.85	0.98	230.2	30207	32
232	16.94	156	14.2	2383	2.6	0.91	0.96	0.93	175.9	52320	19
233	12.69	161	11.6	2430	3.71	1.56	0.9	0.97	204.4	64461	12
234	4.56	200	3.5	2422	3.93	1.55	0.86	0.93	198.1	73350	26
235	6.81	193	15.1	2234	3.05	0.06	1	0.97	236.4	52537	12
236	15.63	189	13.9	2891	2.52	0.63	0.91	0.94	187.6	40396	44
237	14.5	173	13.2	2250	3.34	1.49	0.96	0.99	202.8	36711	40
238	9.44	186	12.1	2016	3.98	1.23	0.92	0.91	176.7	39746	14
239	9.19	174	16.2	2805	4	0.62	0.97	0.95	235.3	29340	15
240	16.63	195	14.8	2180	2.64	0.08	0.87	0.95	182.9	69447	31
241	18.69	196	6.9	2094	3.61	1.46	0.99	0.96	205.6	69664	37
242	9.38	148	20.8	2047	3.14	1.13	0.97	0.91	181.3	50586	44
243	11.81	149	21.2	2844	3.59	0.77	0.86	0.95	215.7	56439	41
244	13	147	24.3	2719	4.8	0.43	0.98	0.94	178.6	42564	18
245	17.69	143	27.8	2297	3.65	1.32	0.86	0.99	249.7	23920	11
246	4.31	159	29.1	2109	4.65	1.27	0.99	0.94	171.2	20668	38
247	11.19	143	25.3	2305	4.32	0.15	0.89	0.96	247.4	50803	31
248	13.56	165	22.6	2984	2.58	0.83	0.95	0.92	161	45816	15
249	13.94	159	20.7	2695	4.63	1.21	0.91	1	206.3	61643	21
250	9	199	29.9	2516	3.07	2	0.91	0.93	166.1	65111	27
251	4.75	173	26.9	2641	4.79	0.88	0.98	0.98	223.5	72266	21
252	13.38	176	24.8	2656	2.79	0.82	0.9	0.91	193.5	23703	34
253	14.88	177	17.7	2789	3.16	1.22	0.93	0.99	210.6	25438	41
254	6	180	23.9	2406	2.97	1.76	0.92	0.92	176.3	34760	17
255	6.5	171	18.5	2609	4.2	0.22	0.95	0.97	216.5	43648	27
256	18.25	174	27.6	2273	4.41	0.25	0.87	0.91	195.4	70098	31
257	19.19	191	28.2	2828	3.01	1.88	0.93	0.97	245.4	53188	35

Low	1	10	500	10	2	0.7	15	0.95	0	10
High	5	30	5000	100	20	1	45	1	2	200
Decimals	0	1	0	0	0	2	1	2	2	1
Design Pt #	AC_LnchAtmpts	AC_LnchIntrvl	JTAC_SnsrRng	JTAC _TLEmu	JTAC_TLEsigma	JTAC_PdC	JTAC_IFTU_Intrvl	WCN_Rel	WCN_Lat	C2_DecTime
170	4	15.9	2768	32	11	0.87	23.9	0.95	1.66	80.5
171	5	19.1	2521	50	12	0.86	28.8	0.97	1.98	43.4
172	2	20.7	1537	33	19	0.98	29.9	0.96	1.32	40.4
173	2	23	922	40	12	0.95	20.2	0.95	1.29	18.2
174	5	16.1	3629	67	10	0.92	18.2	0.96	1.51	35.2
175	4	17.4	3330	59	3	0.94	28.1	0.96	1.72	47.9
176	1	26.2	3084	66	10	0.88	30.2	0.97	1.91	61.2
177	3	24.7	2574	94	8	0.95	19.7	0.97	0.92	84.2
178	1	18.2	3664	26	18	0.78	39	0.99	0.72	27.8
179	2	10.2	4332	45	17	0.72	31.6	0.98	0.75	63.4
180	4	25.9	4402	21	15	0.76	35.7	0.99	0.02	92.4
181	4	21.7	3313	10	11	0.83	36.4	0.98	1.02	79.8
182	2	12.5	1801	80	8	0.82	40.9	0.99	1.04	56.8
183	2	19.7	623	93	4	0.84	38.4	0.98	0.08	54.5
184	5	28.5	746	80	5	0.72	42	0.98	0.84	91.6
185	5	27.3	588	57	12	0.8	33.9	0.99	0.54	22.6
186	1	17.5	605	47	18	0.93	16.1	0.98	0.63	85.7
187	3	19.4	1766	15	13	0.86	18.8	0.97	0.73	74.6
188	3	28.8	535	25	17	0.97	22.5	0.99	0.91	38.9
189	3	22.3	2152	48	17	0.99	28.6	0.98	0.45	77.5
190	3	17.3	4543	60	2	0.89	25.8	0.99	0.1	13
191	2	11.1	5000	53	4	1	17.8	1	0.86	10
192	4	26.6	3102	98	6	0.96	17.6	0.98	1.02	51.6
193	4	20.8	3189	66	8	0.87	26.6	0.99	0.59	44.9
194	5	29.9	4490	67	8	0.95	19	1	0.52	87.2
195	4	29.8	4666	65	6	0.85	24.7	0.99	0.13	13.7
196	2	14.5	3242	90	6	0.88	17	0.98	0.46	37.5
197	3	12	2293	79	6	0.89	28.7	0.98	0.52	107.2
198	4	24.8	2346	15	18	0.89	25.1	0.97	0.55	87.9
199	5	21	1150	23	19	0.89	15.1	0.99	0.45	99.1
200	3	12.1	852	25	20	0.9	32.3	1	0.64	14.5
201	2	14.5	2047	28	19	0.99	18.6	1	0.8	109.5
202	3	21.6	658	83	2	0.78	38.1	0.98	0.47	38.2
203	5	22.7	2117	63	7	0.8	40.1	0.98	0.43	104.3
204	2	16.2	975	56	2	0.74	39.5	0.99	0.56	50.8
205	2	11	1027	83	9	0.77	37.1	0.99	0.41	30.8
206	3	26.3	4631	34	15	0.71	43.7	0.99	0.48	69.4
207	4	21.5	4297	48	20	0.73	44.2	0.99	0.19	12.2
208	2	17.2	4262	46	11	0.79	44.8	0.99	0.36	59.7
209	3	16.6	3172	16	16	0.72	39.3	0.98	0.61	102
210	2	28	3840	72	4	0.97	26.3	0.95	1.7	67.9
211	2	28.1	3541	68	4	0.98	24.4	0.97	1.3	83.5
212	5	19.1	3137	79	5	0.88	21.2	0.97	1.97	53
213	4	19.8	3611	93	3	0.93	21.4	0.96	1.18	42.7
214	2	24.8	781	15	15	0.87	28	0.96	1.4	56
215	2	25.9	2275	29	17	0.95	24.6	0.97	1.73	81.3
216	4	13.9	2803	40	18	0.99	23.1	0.97	1.05	79
217	3	13.3	1133	33	14	0.97	26.5	0.95	1.38	66.4
218	1	19.8	2662	91	8	0.8	40	0.97	1.47	67.1
219	2	28.7	2205	89	9	0.8	40.5	0.97	1.49	93.9
220	4	10.8	1555	59	6	0.78	37.9	0.95	1.78	57.5
221	4	13.1	2645	76	7	0.71	42.5	0.96	1.79	64.2
222	2	27.4	3471	48	12	0.73	38.3	0.95	1.82	48.6
223	3	29.6	4438	20	14	0.75	38.7	0.95	1.77	28.6
224	5	17.8	3787	18	13	0.84	44.1	0.96	1.96	98.3
225	4	15.1	3506	11	13	0.8	30.7	0.95	1.88	34.5
226	4	12.3	3805	33	7	0.83	24	0.95	0.76	128
227	5	18.7	3646	42	9	0.82	34	0.96	0.2	134.7
228	1	23.7	4244	52	6	0.76	23.3	0.96	0.24	133.9
229	2	23.5	4279	40	4	0.85	20.4	0.96	0.97	190.4
230	4	17.7	1309	97	17	0.81	25.2	0.95	0.85	148
231	3	14.8	1625	66	14	0.73	30.6	0.96	0.95	133.2
232	1	21.9	2135	64	13	0.85	28.9	0.96	0.16	136.9
233	2	25.6	1449	76	17	0.77	17.2	0.96	0.78	136.2
234	3	15.5	799	47	5	0.88	40.7	0.95	0.3	185.9
235	3	11.6	939	54	10	0.91	33.3	0.95	1.17	145.1
236	2	21.1	2715	17	6	0.89	40.4	0.97	0.31	180
237	1	25.4	764	60	6	0.94	40.2	0.97	0.14	188.1
238	5	18	3488	61	15	1	41.6	0.97	0.67	162.9
239	3	19.5	4139	98	11	0.86	35.9	0.96	0.05	165.9
240	3	26.5	4613	55	13	0.91	32.8	0.96	0.63	168.8
241	2	20.1	4596	81	18	0.91	39.7	0.97	0.77	144.3
242	1	18.4	4016	26	3	0.72	23.4	0.98	1.26	170.3
243	2	13	2961	10	9	0.83	16.8	0.97	1.09	137.7
244	4	29.7	4982	41	5	0.79	17.3	1	1.34	192.6
245	4	23.3	2891	42	2	0.8	25.5	0.97	1.68	141.4
246	3	14.2	1643	69	16	0.74	22.3	0.98	1.35	131.7
247	2	12.9	641	82	19	0.74	27.4	1	1.07	180.7
248	4	23	2064	92	16	0.77	17.7	0.98	1.43	113.2
249	5	22.4	729	53	13	0.76	26.4	0.98	1.61	151
250	2	10.5	1783	12	8	0.95	36.2	0.98	1.59	163.6
251	2	18	2381	35	4	0.99	31.8	0.98	0.99	127.3
252	4	26.4	3066	22	6	0.91	37.4	0.98	1.75	160.7
253	5	27.2	1502	35	11	0.86	44.6	0.98	1.67	173.3
254	1	10.7	3980	88	12	0.91	38.9	1	1.88	177
255	1	18.6	2996	82	12	0.98	43.4	0.98	1.56	156.2
256	3	25.7	3594	80	19	1	36.8	0.98	1.06	198.5
257	4	26.8	4174	73	15	0.83	30.4	0.98	1.89	199.3

APPENDIX C. CALCULATING AN EXPECTED VALUE OF THE RESPONSE VARIABLE BASED ON REGRESSION COEFFICIENTS

The two tables below show the regression coefficients and corresponding scaled estimates for a regression model with five terms (plus the intercept term). If given the parameter coefficients (top table), the formula for calculating an estimate of the response is simply obtained by adding the intercept term to the sum-product of the regressor terms and their corresponding assigned value. For example, by selecting values for the five terms in this model (within the ranges of the original design) and inserting them into the formula below, an estimate of the response is obtained—in this case, the proportion of mobile vehicle target kills.

(-0.424164) + (-0.062232 * Tgt_C_Spd) + (0.0048507 * NEW_ImpRad) + (0.9302622 * NEW_PdC) + (0.001617828 * AC_Spd) + 0.0001395 * JTAC_SnsrRng)

If given the scaled estimates, a conversion must be made to obtain the original parameter estimates. As indicated in the bottom figure, the estimates are centered by mean and scaled by range/2. This indicates the scaled estimate was obtained by multiplying the original coefficient by the value of (range of factor setting)/2. For example, in the design, target speed varied between 4 and 20 m/s. This provides a range/2 value of (20–4)/2 = 8. Multiplying the original coefficient estimate for target speed by 8 gives the value of the scaled estimate (rounding considered):

(- 0.062232) * 8 = –0.497856.

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-0.424164	0.42449	-1.00	0.3186
Tgt_C_Spd	-0.062232	0.004021	-15.48	<.0001
NEW_ImpRad	0.0048507	0.002382	2.04	0.0428
NEW_PdC	0.9302622	0.427881	2.17	0.0306
AC_Spd	0.0016178	0.000643	2.51	0.0125
JTAC_SnsrRng	0.0001395	0.000014	9.75	<.0001

Scaled Estimates

Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.4830739	0.018645	25.91	<.0001
Tgt_C_Spd	-0.497853	0.032169	-15.48	<.0001
NEW_ImpRad	0.0654849	0.032162	2.04	0.0428
NEW_PdC	0.0697697	0.032091	2.17	0.0306
AC_Spd	0.0808914	0.032169	2.51	0.0125
JTAC_SnsrRng	0.3137775	0.032169	9.75	<.0001

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APPENDIX D. ANNOTATIONS REGARDING APPLICABILITY OF MODEL IN ADDRESSING OVERALL JTEM REQUIREMENTS

JTEM Requirement		Resolution within "TheTester"
Identifier	**Description**	**Developer Comments**
1	Ability to model JTEM Test 07 and JTEM Test 08 scenario and its associated entities. The ABM should be designed to model at least the JTEM Test 07 and JTEM Test 08 scenarios	
1.1	Task Force organizations to support the scenario	P - I don't know what these are yet to make a further assessment. We have Aircraft (Launch Platform), NEW, Legacy, C2ISRNetwork (assigns CAS missions to aircraft based on Target classification and priority and weapon-target pairing), and WCNetwork (models latency and reliability of target updates getting from JTAC to NEW)
1.2	The Army's None-Line-Of-Site Launch System (NLOS-LS) platform with its Precision Air Munitions (PAMs), including ability to vary platforms, PAM mix, and PAM range	N - although if the NLOS-LS can be modeled using the current Aircraft Agent, than Y. We'd need more information on what constitutes this package of systems.
1.3	The Air Force's Networked Enabled Weapon (NEW) and its delivery air platforms, including ability to vary platforms, NEW mix, and NEW range	Y - this was the canonical scenario. Again, depends on what is included in the "delivery air platforms"
1.4	Joint Command and Control (JC2) entities with at least Joint Tactical Air Control (JTAC) elements (ability to vary types) and a representation of the Joint Force Commander and staff. For the purposes of this ABM effort, this latter representation should be kept simple, providing a minimal number of representatives (e.g., the Joint Force Commander, the Joint Force Air Component Commander, the Joint Force Land Component Commander, and Joint Force Effects Coordination Cell) to accomplish JC2 with respect to the NLOS-LS and NEW systems	N/P - not sure how modeling the Commanders will impact the system. Will need more information on this to answer fully. However, the current C2ISRNetworkAgent only models latency in decision time, and the decision modeled is the assignment of aircraft to a CAS mission.
1.5	Appropriate enemy targets (including types/speeds of targets) to support the test scenario	Y. Stationary and mobile Targets are modeled, with each having a target class that can represent different types of targets. For mobile targets, you specify a path and a speed. The target class is also linked to Pd and Pk for the JTAC/NEW sensors and the NEW
1.6	Ability of enemy to jam PAM and NEW systems	N. Would need to know the different ways jamming effects the systems ,e.g., does it change the Pd, add noise to the TLE, other mechanisms?
1.7	Ability to model unit order of battle	P. User can add any number of agents (other than C2ISRNetworkAgent) by adding them to the scenario file. Would need more testing, though.
1.8	Able to vary Blue and Red materiel, doctrine, organizations, personnel, and leadership	P. Only material, personnel, and organizations, and personnel and organizations only by number. Would need to add different types of doctrinal "behaviors" to capture this fully. I think this is one area where we'd need to discuss future efforts
1.9	Clutter (e.g., civilian personnel, air traffic) to evaluate its impact on system performance operations (e.g., deconfliction of air space for launching the NLOS-LS or NEW)	N. Would need more information on what needs to be modeled and what interactions there are
1.10	Ability to change type of mission	P. Only one type of mission, but can be adapted.
1.11	Ability to add conceptual models of new systems	N. Certainly something to be done for future effort. Would need some design work so that conceptual models could easily be "plugged-in"
1.12	Ability to model rules of engagement (ROEs)	N/P. ROEs, in a limited sense, are "hard-wired". The JTAC senses a Target, "knows" it is one, and then sends CAS request, which then gets prosecuted for that target. There is a Redirect by the JTAC if a target of higher priority presents itself. Currently, the only thing I would call an ROE that is implemented.

JTEM Requirement		Resolution within "TheTester"
Identifier	**Description**	**Developer Comments**
2	Ability to model/assess JC2	
2.1	Model/assess shared situational awareness, planning, conduct of netcentric operations, and C2 efficiency	N. Would need some kind of conceptual model to start with. The other question, is what part of all of THAT system affects the system under test? In the larger sense of modeling systems of systems, I guess it depends on what's getting tested and where the connections are, and what of the larger system affects those connections.
2.2	Ability to conduct battle damage assessment	N. BDA is not performed, nor information from a BDA inserted into the overall system.
2.3	Consider NATO Code of Best Practices for C2 Assessment, published by the Command and Control Research Program (CCRP) under the auspices of the Assistant Secretary of Defense (C3I), 2002	
3	Ability to model/assess sensor systems	N/P. The only set of "sensors" in the model are those attached to the JTAC and the NEW
3.1	Unattended ground sensors	
3.2	Sensors mounted on unmanned ground and air platforms	
3.3	Sensors on NLOS-LS/PAM and NEW systems	
3.4	Sensors for NLOS operator and JTAC (including target location system)	
4	Ability to model/assess the Joint Fires (including Joint Close Air Support) and JC2 Doctrine/TTPs to support the above scenarios, include ability to	
4.1	Vary doctrine/TTPs	N
4.2	Manage the air space	N
4.3	Model impacts on Circular Error Probable (CEP) for weapon systems	P - Have included TLE mu/sigma for the NEW
4.3.1	NEW update rates	Y
4.3.2	NEW-Link16 latency	Y - Latency and Reliability of the link are modeled using uniform distributions
4.3.3	JTAC effectiveness (beam blocked, beam split, environmental effects)	P - Only to the extent that the JTAC is tracking the target using the sensor, that includes TLE mu/sigma factors
4.3.4	Relative CEP	N - Model uses bivariate Normal TLE approximation
4.3.5	C2 issues	P - Addresses latency associated with C2 time to respond to CAS request
5	Ability to model/assess netcentric communications systems, including the ability to:	
5.1	Track message traffic	N
5.2	Degrade system effectiveness with effects of weapons and environment	N
6	Ability to model the environment, including	
6.1	Representation of the terrain where tests will occur	N - How does terrain affect the system?
6.2	Features (e.g., buildings, foliage) and weather, or at least the effects that features and weather have on system of systems performance and TTPs	N/P - Currently modeled by varying the Pd and TLE of the JTAC or NEW
6.3	Visibility	N/P - Same as 6.2
6.4	Civilians	N
7	Ability to mode/assess some human dimensions:	
7.1	For message traffic received by a human, add ability to adjust the understanding of the message (this may be as simple as “understand” and “does not understand”)	N
7.2	Variable operating skills for the JTAC and NLOS personnel	N/P - Throught the Pd/TLE and IFTU frequency currently
7.3	Civilian relationships to Blue and Red	N - Neutrals currently not modeled
7.4	Ability to affect human performance (e.g., information/message overload slows down decision processes or causes an action to be missed altogether)	N/P - Currently, only in C2 decision latency

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